REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Report 7701	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FRACTURE TOUGHNESS CHARACTERIZATION OF SHIPBUILDING STEELS		5. TYPE OF REPORT & PERIOD COVERED Final report on one phase of the problem; work continuing. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. R. Hawthorne and F. J. Loss		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 63 M01-25 RR 022-01-46-5432
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Navy Office of Naval Research Arlington, Va. 22217		12. REPORT DATE July 10, 1974 13. NUMBER OF PAGES 46
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Shipbuilding steels
Fracture toughness
Fracture-safe assurance criteria
Dynamic tear test
Drop weight-NDT test
Charpy V-notch test
Fracture mechanics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

New fracture control guidelines for welded ship hulls have been proposed as a result of an investigation sponsored by the Ship Structure Committee of the Maritime Transportation Research Board. These guidelines include fracture toughness requirements in terms of the Drop Weight-NDT temperature and Dynamic Tear (DT) energy. To aid the implementation of these criteria an exploratory program was undertaken to characterize the dynamic fracture toughness of ordinary-strength shipbuilding steels, namely, ABS Grades A, B, C, D, E, and CS. Test materials (plate) were obtained at random from several shipyards and steel mills in an

20. Continued

effort to characterize the products of current steel making practice. Fracture toughness trends were defined by means of Drop Weight-NDT, 1-in. DT and standard Charpy V-notch tests and the observed toughness characteristics were compared with the proposed toughness criteria. Non-heat treated plates of ABS Grades A, B, and C were found to have insufficient toughness to meet reasonable fracture toughness requirements. On the other hand, normalized plates of ABS Grades C, D, E, and CS were found to exhibit improved toughness trends that could meet the proposed requirements in most cases.

CONTENTS

INTRODUCTION 1

PROGRAM SCOPE 2

MATERIALS 2

TEST SPECIMENS AND PROCEDURES 5

DROP WEIGHT NDT RESULTS 8

GENERALIZED INTERPRETATION OF DT ENERGY 10

DT TEST RESULTS 14

CHARPY-V RESULTS 25

GRADE AH AND EH ASSESSMENTS 34

RELATIONSHIP OF MEASURED NOTCH TOUGHNESS TRENDS TO RECOMMENDED FRACTURE CONTROL GUIDELINES 34

NDT Criterion 34
Toughness at Minimum Service Temperature 35
DT Energy Criteria 36

RECOMMENDATION FOR FOLLOW-ON RESEARCH 37

Crack Arrester Materials 37
Thickness Effects 38
Metallurgical Effects 38
Higher Strength (H) Grades 39
K_{Id} Trends 39

SUMMARY AND CONCLUSIONS 39

ACKNOWLEDGMENTS 41

REFERENCES 41

ABBREVIATIONS AND SYMBOLS 43

FRACTURE TOUGHNESS CHARACTERIZATION OF SHIPBUILDING STEELS

INTRODUCTION

With the advent of the supertanker and of ships carrying liquefied natural gas (LNG), questions of the fracture safety assurance of the ship's hull have assumed increased importance. In the United States commercial shipbuilding steels have been classified by the American Bureau of Shipping (ABS) according to chemistry, strength level, and heat treatment. The ABS steel grades for ordinary-strength hull applications are A, B, C, D, E, and CS. Specific fracture toughness requirements for these steels, as related to service performance, are not included in existing specifications but are under consideration by ABS. In current applications, adequate toughness is inferred through controls on chemistry, deoxidation practice, and heat treatment. The past record of good fracture-safe performance of ships has been achieved through experience with the individual grades coupled with knowledgeable ship design and fabrication practices. Nevertheless, occasional castastrophic fractures have occurred to suggest a need for improvement in fracture-safe assurance procedures.

Recognizing the above, the Ship Structure Committee (SSC) of the Maritime Transportation Research Board recently commissioned a study by Rolfe and coworkers [1] to develop fracture control guidelines for welded steel ship hulls based on existing technology. In their report to the Committee, Rolfe and coworkers stated a need to define the toughness of shipbuilding steels directly by means of a fracture toughness test rather than indirectly through specification of chemistry and heat treatment. Specifically, they recommended that all steels and weldments used in primary load-carrying members in the main stress regions of ships should exhibit a maximum Drop Weight-Nil Ductility Transition (NDT) temperature of 0° F (−18° C) as measured by ASTM Standard Test Method E-208. Furthermore, they recommended the requirement of fixed 5/8-in. Dynamic Tear (DT) test [2, 3] energy levels at room temperature. This requirement was formulated to assure an increase in toughness with rising temperature above the 0°F NDT criterion so that acceptable toughness is exhibited at a minimum service temperature of 32° F (0° C). The DT test is currently a military standard, Mil Std 1601 SHIPS, and is being actively investigated by ASTM Committee E-24 on Fracture Testing of Metals for the purpose of defining a standard DT test method.

The DT test procedure provides a means for rational interpretation of fracture toughness trends whereby structural performance can be projected. This structural translation generally is not possible using the Charpy V-notch (C_v) test of long standing. Charpy energy minima presently are required by ABS specifications for Grades D and E, but the values are considered by the authors to provide only limited assurance of a consistent quality steel; the C_v numbers themselves cannot be related to fracture-safe performance in a consistent manner.

Note: Manuscript submitted December 3, 1973.

At the time of Rolfe's recommendation of the DT test as a preferred method of plate toughness qualification, an extensive DT characterization of shipbuilding steels did not exist. Therefore, to aid in the implementation of proposed DT requirements, SSC requested that NRL develop a DT data bank, semistatistical in nature, for ordinary-strength hull steels. This report describes the resultant NRL investigations which include, in addition to DT characterizations, determinations of NDT temperature distributions and selected C_v comparisons for the steels in question. The goals of the study were to provide to the SSC early information of sufficient scope to clarify the new (proposed) criteria and to establish realistic objectives for later, more comprehensive studies. The subject program accordingly was formulated as a first-stage, statistical exploration of fracture properties with limited objectives. The program time frame was six months.

PROGRAM SCOPE

The program plan was to procure plate sections from both steel producers and shipyards which would represent a random sampling of ABS Grades A, B, C, D, E, and CS. The samples were to be representative of current mill practice and were to be obtained in sufficient numbers to infer the range in toughness to be expected for a given grade. Accordingly, a goal of 5 to 7 samples per grade from different sources was set forth. Only plates of 1-in. thickness were considered; this thickness is commonly used in ship construction and, accordingly, was assumed to be readily available from the different mills and shipyards. In this regard, a characterization of fracture toughness as a function of thickness was considered to be a valid objective but of secondary importance to the primary definition of DT toughness characteristics for the individual grades of steel. The effect of plate thickness was not explored in the subject program.

All plates were to be evaluated by the 1-in. DT test method wherein a full brittle-ductile transition curve of DT energy vs temperature would be established. Likewise, NDT temperatures of all steels were to be established using the Drop Weight test. Charpy-V curves were to be developed only for those plates that appeared to exhibit the highest and lowest NDT or DT toughness within a given ABS grade.

MATERIALS

Program materials were obtained from seven steel companies and five shipyards. Several of these plates were obtained through ABS liaison. The plates investigated in the program are listed according to source, ABS grade, and composition in Table 1. Identification of a given plate by specific supplier has been intentionally omitted and the materials are referenced only by an NRL code number. All plates were produced in the United States, however. The mechanical properties are given in Table 2. Average yield and tensile strength values were approximately 37 and 63 ksi, respectively, for the non-heat-treated plates of ABS Grades A, B, and C. In comparison, the heat-treated (normalized) plates of Grades

Table 1
Identification, Source, and Chemical Composition of Test Plates

Material Type	Plate (Code)	Thickness (in.)	Source	Mill	Chemical Composition (wt-%)*				
					C	Mn	P	S	Si
ABS-A	U-11†	2.0	D	E	0.19	0.42	0.004	0.025	0.23
	U-13	0.75	B	B	0.21	1.02	0.007	0.019	0.01
	U-23	1.0	A	A	0.16	0.57	0.003	0.026	0.22
	U-25	0.8	C	C	0.16	0.68	0.007	0.023	0.06
(AH)	U-31	1.0	A	A	0.19	1.41	0.004	0.017	0.26
ABS-B	U-14	1.0	B	B	0.20	1.00	0.005	0.023	0.008
	U-20	1.0	D	‡	0.12	0.87	0.007	0.025	0.15
	U-21	1.0	A	A	0.10	1.01	0.005	0.019	0.19
	U-26	0.88	C	C	0.15	1.06	0.005	0.027	0.04
	U-33	1.0	E	E	0.17	0.80	0.004	0.030	0.17
	U-34	1.0	F	D	0.15	0.93	0.006	0.013	0.01
ABS-C	U-10	1.0	D	A	0.14	0.72	0.004	0.018	0.19
	U-15	1.0	B	B	0.15	0.74	0.012	0.019	0.22
	U-27	1.0	C	C	0.15	0.70	0.006	0.029	0.18
	U-35	1.25	F	D	0.22	0.83	0.013	0.020	0.23
	U-12	1.0	A	A	0.15	0.82	0.008	0.028	0.25
ABS-C (NORM)	U-22	1.0	A	A	0.14	0.81	0.008	0.029	0.28
	U-19‖	1.5	G	F	0.17	0.68	0.009	0.025	0.21
	U-89‖	1.0	B	B	0.18	1.06	0.013	0.014	0.25
	U-93‖	1.63	H	C	0.12	0.66	0.010	0.022	0.21
ABS-D (NORM)	U-17	1.0	B	B	0.22	0.75	0.016	0.024	0.27
	U-29	1.0	A	A	0.08	1.16	0.010	0.020	0.22
	U-90‖	1.0	B	B	0.14	1.03	0.011	0.027	0.28
	U-95‖¶	1.0	H	G	0.19	0.89	0.010	0.018	0.22
ABS-E	U-18**	1.0	B	B	0.24	0.75	0.017	0.027	0.26
	U-28	0.75	C	C	0.11	1.08	0.006	0.019	0.19
	U-30	1.0	A	A	0.07	1.23	0.007	0.019	0.19
(EH)	U-32	1.0	A	A	0.18	1.41	0.005	0.019	0.26
ABS-CS	U-16	1.0	B	B	0.18	1.02	0.010	0.019	0.19
	U-24	1.0	A	A	0.07	1.20	0.007	0.018	0.21
	U-96	1.0	H	‡	‡	‡	‡	‡	‡

* NRL determination except as noted.
‡ Not known.
‖ Chemistry courtesy ABS.
¶ Not normalized.
† Mill test report showed 0.18C, 0.48 Mn, and > 2.5 Mn/C ratio.
** Mill test report showed 0.16C, 1.00 Mn, with grade E certification.

Table 2
Mechanical Properties of Test Plates*

Material Type	Plate (Code)	Thickness (in.)	YS†‡ (ksi)	TS (ksi)	RA (%)	Elong. (in 2-in.) (%)	Drop Weight NDT		50% DTE Temperature		DT Energy (avg ft-lb)‖ at				Charpy-V Energy (avg ft-lb)‖ at	
							(°F)	(°C)	(°F)	(°C)	NDT	NDT + 30°F	NDT + 60°F	DT Shelf	NDT	C_v Shelf
ABS-A	U-11	2.0	29.2	58.8	64.4	34.5	50	10	135	57	< 490	1000	1950	6000	13	80
	U-13	0.75	39.2	64.7	68.3	37.0	20	−7	95	35	360	640	1400	4700	≈20	87
	U-23	1.0	37.7	63.0	64.6	35.0	40	4	130	54	440	850	1800	5750	—	—
	U-25	0.8	39.3¶	59.1	68.7	37.0	20	−7	95	35	420	630	1250	5700	—	—
(AH)	U-31	1.0	47.8	80.5	69.7	30.5	20	−7	125	52	450	600	1200	6050	—	—
ABS-B	U-14	1.0	32.1	65.4	68.2	36.0	30	−1	120	49	450	850	1700	6400	14	95
	U-20	1.0	37.3	62.8	70.0	35.0	20	−7	125	52	340	600	1400	7100	—	—
	U-21	1.0	36.2	62.8	71.7	37.0	30	−1	125	52	550	1050	2000	7500	14	137
	U-26	0.88	41.9	66.4	69.7	35.5	20	−7	110	43	270	600	1400	6000	—	—
	U-33	1.0	40.3	62.1	67.2	35.8	20	−7	80	27	520	1080	3000	5880	—	—
	U-34	1.0	32.4	58.5	69.4	39.3	30	−1	110	43	490	1050	1850	6600	—	—
ABS-C	U-10	1.0	36.6	63.9	64.6	33.8	20	−7	130	54	< 500	600	1400	~8100	~44	131
	U-15	1.0	35.0	65.2	65.1	35.0	30	−1	105	41	570	780	1900	6300	—	—
	U-27	1.0	40.6	63.5	64.4	35.0	10	−12	85	29	310	610	1900	6250	17	96
	U-35	1.25	41.6	71.9	59.4	32.3	20	−7	115	46	680	950	1780	7550	—	—
	U-12	1.0	39.2	63.8	67.4	35.0	10	−12	110	43	400	~750	1600	6150	24	107
ABS-C (Normalized)	U-22	1.0	46.6	64.4	70.7	36.5	−30	−34	55	13	480	800	2000	~7000	63	120
	U-19	1.5	36.5	62.7	65.1	36.0	−10	−23	70	21	580	820	1860	≥9000	—	—
	U-93	1.63	40.1	59.7	67.8	37.0	−10	−23	75	24	650	890	1740	≥9000	—	—
	U-89	1.0	49.8	70.8	69.1	35.0	−20	−29	—	—	—	—	—	—	—	—
ABS-D (Normalized)	U-17	1.0	43.0	66.7	64.6	36.0	20	−7	90	32	320	710	2050	6050	29	89
	U-29	1.0	41.4	63.0	74.1	37.5	0	−18	95	35	320	840	2000	>9000	—	—
	U-90	1.0	46.2	65.1	73.4	37.5	−30	−34	15	−9	550	1450	7930	7930	—	—
	U-95**	1.0	52.0	72.1	66.4	33.0	−20	−29	60	16	330	940	2150	6840	—	—
ABS-E	U-18††	1.0	44.1	71.0	61.7	33.5	20	−7	110	43	340	550	1370	5900	22	93
	U-28	0.75	45.5	62.4	76.0	39.5	−40	−40	−15	−26	650	4000	5750	5750	80	144
	U-30	1.0	40.9	61.4	78.6	39.0	−10	−23	70	21	540	1500	3000	>9000	—	—
(EH)	U-32	1.0	54.6	77.4	72.9	33.8	−60	−51	35	2	760	1190	2450	>9000	—	—
ABS-CS	U-16	1.0	43.1	65.6	70.3	37.0	−20	−29	45	7	570	900	2780	7300	—	—
	U-24	1.0	43.2	60.4	78.3	40.0	−10	−23	~60	16	~700	3000	4450	>9000	>200	>200
	U-96	1.0	54.4	71.4	72.2	35.0	−40	−40	−10	−23	560	3000	7000	7000	—	—

* NRL determinations except where noted.
† 0.505 diam specimens, duplicate tests.
‡ Multiply by 6.9 to obtain newtons per square meter $\times 10^6$, MN/m^2.
‖ Multiply by 1.36 to obtain joules, J.
¶ Single determination.
** Not normalized.
†† Did not meet C_v specifications for Grade E.

C, D, E, and CS exhibited somewhat higher average yield strengths than the non-heat-treated plates but essentially the same tensile strength.*†

Composition limits, tensile properties, and heat-treatment procedures for ship hull steels are defined by ABS Rules [4]. The data in Tables 1 and 2 confirm that the program plates met these requirements with only one exception, as discussed below. Additional test requirements, i.e., C_v test, are set forth by ABS Rules for Grade D (35 ft-lb and 23 ft-lb at 32°F 0°C, longitudinal and transverse orientations, respectively) and for Grade E (45 ft-lb and 30 ft-lb at 14°F −10°C, longitudinal and transverse orientations, respectively.) All plates, according to mill test evaluations, satisfied the additional C_v energy requirements. Although Plate U-18 was obtained directly from a mill and was mill-certified as Grade E, NRL results for this plate indicated a below-specification C_v energy level and carbon content.

In this report, Grade C plates are treated separately according to heat treatment received. The designation, Grade C, will refer to as-rolled plates; the designation, Grade C-norm will denote heat-treated (normalized) plates. Grade D plates are not treated separately according to heat treatment received; the designation Grade D will refer to as-rolled plate while the designation, Grade D-norm, will denote heat-treated plate. The Grade D specification does not require heat treatment.

TEST SPECIMENS AND PROCEDURES

The size** of the DT test specimen employed was 4 in. (width) by 18 in. (length) by full plate thickness. The specimen contained a 1-in.-deep machined notch‡ and an unbroken ligament of 3 in. For plates thinner or thicker than the nominal 1 in., these planar dimensions were maintained. The specimen notch tip was sharpened by pressing-in a knife blade (40-degree included angle) approximately 0.010 in. Notch acuity was confirmed using a 60 X shadowgraph. A minimum of six specimens was used to establish the full curve of DT energy versus temperature for a material. The single pendulum impact machine used for the tests was of 10,000 ft-lb capacity.

The dimensions of the described DT specimen are generally those of the 1 in. standard DT specimen. However, the specimen width was reduced to 4 in. from 4-3/4 in. in order to conserve material. The unbroken ligament was unchanged; only the notch was shortened from 1-3/4 in. to 1 in. To determine the effect on energy absorption resulting from this specimen modification, a comparison study of the 4 in. vs the 4-3/4 in. wide reference specimen was made. The results of the study, illustrated in Fig. 1, show no difference in energy absorption between the two specimens over the full transition range. It is therefore considered

* The range in yield strength values was 29.2 — 52.0 ksi for non-heat-treated plates and 36.5 — 54.4 ksi for heat-treated plates (excepting two AH and EH plates).

† The range in tensile strength values was 58.5 — 72.1 ksi for non-heat-treated plates and 59.7 — 71.4 ksi for heat-treated plates (excepting two AH and EH plates).

** The test program using the 1-in.-thick DT specimen was well underway at the time the 5/8-in.-thick DT specimen was recommended to be the standard for ship plate toughness characterization (1).

‡ The machined notch as 1/16 in. wide and had a 60° V notch tip.

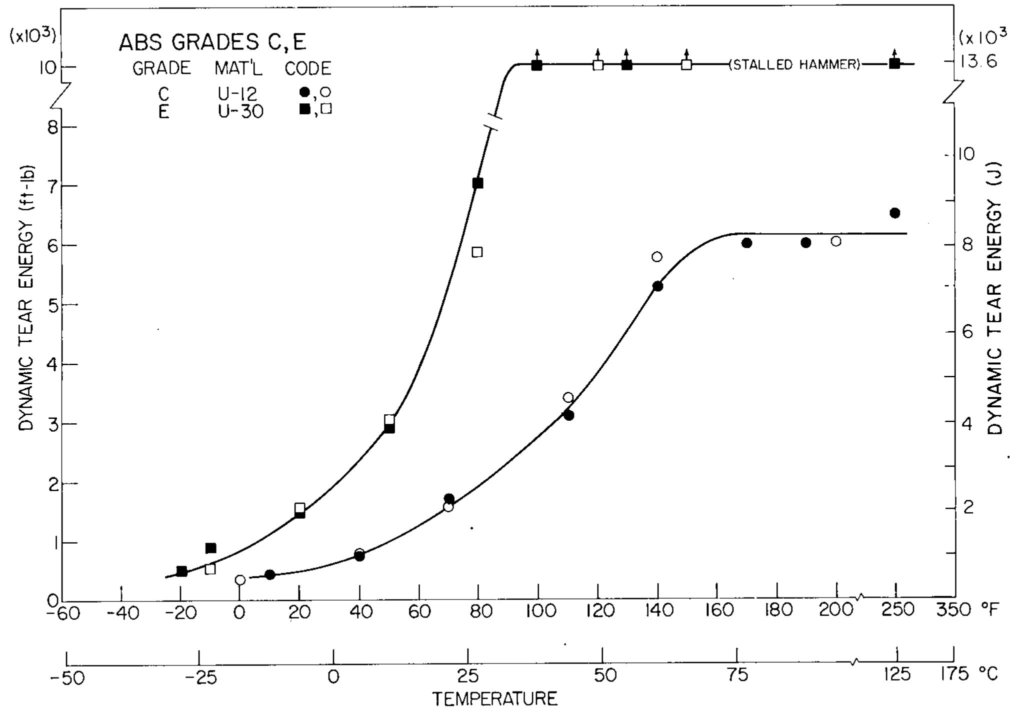

Fig. 1 — Comparison of test results from modified (4-in. wide) and reference standard (4-3/4 in. wide) DT specimens (filled vs open points, respectively). The change in specimen notch depth (1 in. vs the 1-3/4 in. of the reference standard) is shown not to have an effect on DT performance over the full transition range.

that results from this DT characterization of hull steels may be compared directly with published results for other steels that were characterized with the standard 4-3/4-in.-wide DT specimen.

The Type P-2 ASTM Drop Weight specimen[1] (2 in. by 5 in. by 3/4 in. thick) was used for determinations of NDT temperatures as per ASTM Standard Procedure E-208. Tests were conducted using a 60-lb falling weight released from a 5-ft drop height. The anvil of the tester had a 4-in. span and allowed 0.060-in. (max) specimen deflection. The crack starter weld was applied to the specimen saw-cut surface in this study rather than to the as-rolled surface (required in the ASTM specification) to avoid any surface effects and to best determine bulk NDT properties for planned DT data comparisons. As is discussed later in this report, test comparisons conducted by NRL and by the ABS laboratory using several program plates indicated that the choice of surface for the crack starter weld was not critical for the types of materials investigated here.

Two tensile specimens (0.505-in. diam by 2.0 in. gage length) were taken from each plate. Yield strengths were determined from extensometer traces. Standard C_v specimens were normally taken from two plates per grade which depicted the extremes of NDT performance or, secondarily, of chemistry variation. The C_v specimens were taken adjacent to the plate surface and in the same orientation as the DT specimens. The impact tester employed was of 264 ft-lb capacity and was calibrated in advance with standard specimens obtained from the Army Materials and Mechanics Research Center, Watertown, Massachusetts.

In all cases the standard specimen orientation was the RW orientation (longitudinal, parallel to the primary plate rolling direction). This orientation was selected as best approximating the most likely potential fracture path in a hull. The rolling direction of each test plate was verified by NRL using macroetching procedures. It should be noted that test-plate sizes, as received, were nominally on the order of 2 ft by 3 ft; therefore, it is considered that any metallurgical variations would be small and so all test results for a given plate can be compared directly. Experimental results from all impact tests are summarized in Tables 2 and 3.

Table 3
NRL-ABS Comparison Study of Drop Weight NDT Performance*

Plate	ABS Grade	Specimen Group	Weld Surface†	Welded	Tested	NDT (°F)
U-23	A	1	SC	NRL	NRL	40
		2	SC	NRL	ABS	40
		3	AR	ABS	ABS	10
		4‡	AR	NRL	NRL	40
U-12	C	1	SC	NRL	NRL	10
		2	SC	NRL	ABS	10
		3	AR	ABS	ABS	10
U-17	D NORM	1	SC	NRL	NRL	20
		2	SC	NRL	ABS	20
		3	AR	ABS	ABS	10
U-16	CS	1	SC	NRL	NRL	−20
		2	SC	NRL	ABS	−30
		3	AR	ABS	ABS	−30
U-11	A	¶	AR	NRL	NRL	50
			SC	NRL	NRL	50

* All specimens were Type P-2.
† SC = saw cut, AR = as rolled.
‡ Additional specimen group for clarification of group 3 anomolous results.
¶ Not part of comparison study.

DROP WEIGHT NDT RESULTS

Figure 2 shows the NDT temperature trends observed for the individual ABS grades examined. Six or more specimens were generally involved in each NDT determination. At least two, and normally three, specimen tests were used to confirm the minimum no-break test temperature. In the majority of cases, a clear definition of NDT was obtained from consistent break/no-break performance between two specimens over a 10°F interval. In all cases it was apparent that NDT temperatures could be readily established to an accuracy of 10°F (6°C).

Figure 2 indicates that all Grade A, B, and C plates evaluated had NDT temperatures above 0°F. The average NDT temperature for each of these grades appears to be 20°F to 30°F. As expected, the heat-treated grades (C-norm, D-norm, E, and CS) tended toward lower NDT temperatures. It can be projected from the data that a majority of the heat-treated grades will pass the 0°F (max) NDT requirement proposed by Rolfe [1]. However, the 20°F NDT temperature exhibited by the D-norm plate (U-17) suggests that exceptions to this generalization will occur. Plate U-17 is considered to have met the ABS C_v requirements of 35 ft-lb at 32°F (0°C), the average of five NRL tests (RW orientation) was 35.2 ft-lb.

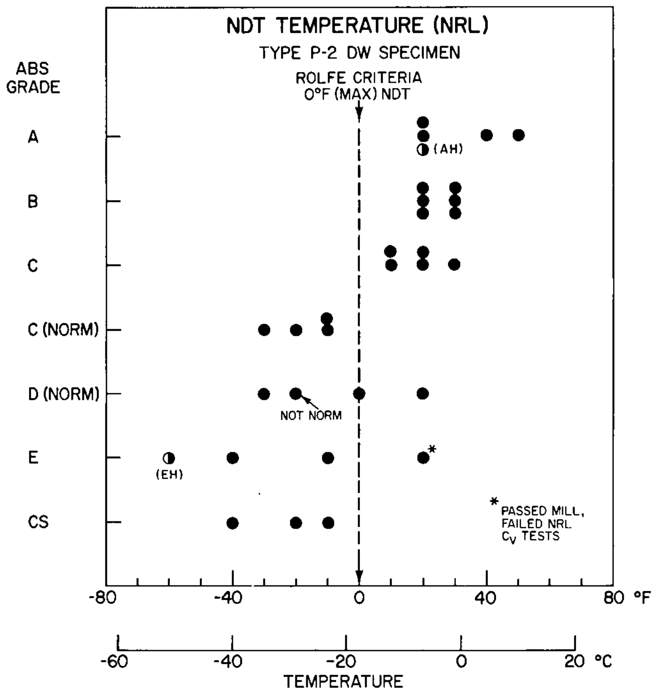

Fig. 2 — Summary of NDT temperatures. Note that all of the ABS Grade A, B, and C plates fail the 0°F (−18°C) maximum NDT criteria proposed by Rolfe for ordinary-strength hull steel.

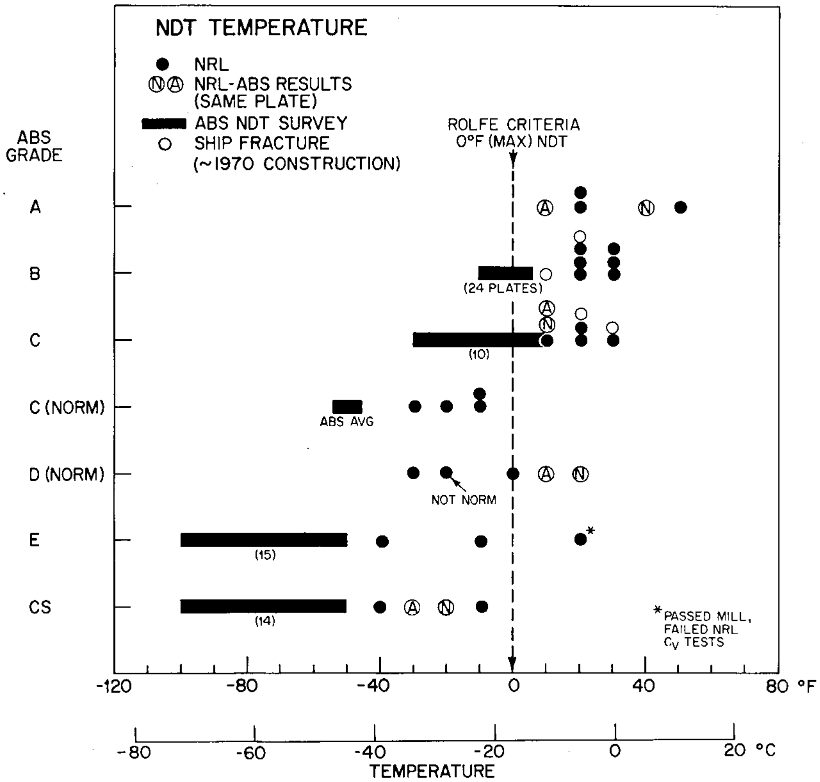

Fig. 3 — Comparison of NDT temperature distributions observed in the present study and in an earlier ABS study. Results of an NDT comparison study by NRL and ABS (same plates) are identified. Also illustrated are the NDT temperatures of material taken along the fracture path of a recent ship failure.

Results from an earlier survey of NDT performance by ABS [5] on five of the grades are compared to NRL findings in Fig. 3. For all grades, the ABS results describe consistently lower NDT temperatures than those observed in the present study. It is of additional significance that the data scatter bands for the two investigations do not overlap. If the NDT temperature measurement techniques of NRL (present study) and the ABS laboratory (earlier study) are assumed to be consistent, then the results of Fig. 3 suggest a difference in the toughness of the ABS grades between the times of the two surveys. It is clear that follow-on studies to identify the causes of the poorer NDT performance found by the present study are desirable.

Figure 3 illustrates the NDT temperatures of Grades B and C plate material taken along the fracture path of a recent ship fracture. The fact that the NDT temperatures of currently produced Grades B and C are equivalent to these ship plate NDT temperatures suggests that material of higher toughness may be required to insure fracture-safe operation.

In an attempt to explain the difference in average NDT temperature for a given grade, as determined by NRL and ABS, it was suggested that the answer might be associated with the location of the weld bead (i.e., on the saw-cut surface as employed by NRL as opposed to the as-rolled surface as employed by the ABS laboratory in accordance with the ASTM specification). However, for the types of steels being considered, one would not expect the placement of the weld bead with respect to either of the specimen surfaces to be significant.* Nevertheless, two groups of Drop Weight specimens from a 2-in.-thick Grade A steel (U-11) were tested by NRL. One group had the weld bead on the as-rolled surface and the other group had the weld on the saw-cut surface. The results from both sets of specimens were identical, thereby confirming the above assumption. Finally, a comparison NDT study using common material was undertaken between NRL and the ABS laboratory. The variables considered in the study were (a) weld-bead placement with respect to as-rolled vs saw-cut surface, (b) weld-bead deposit technique, and (c) test technique. The exchange involved three groups of Type P-2 specimens cut from four materials, namely, ABS Grades A, C, D-norm, and CS. Group 1 specimens were welded by NRL on the saw-cut surface and tested by NRL. Group 2 specimens were also welded on the saw-cut surface by NRL but tested by ABS, whereas Group 3 specimens were welded by ABS on the as-rolled surface and subsequently tested by ABS. Results of this study are summarized in Table 3 and Fig. 3.

Correspondence within 10°F is noted between NDT temperatures determined from Group 1 and Group 2 specimens, thereby suggesting no significant differences in test technique between the two laboratories. A good correlation is also noted between groups 2 and 3 (one apparent exception), all of which were tested by ABS. This correlation suggests that there exists no difference attributable to the surface on which the weld bead was placed or the weld deposit technique. An apparently anomalous difference of 30°F in NDT temperature between Groups 2 and 3 was observed for the Grade A material (U-23). Noting that since the Group 1 vs Group 2 comparison for this plate gave identical results, the 30°F difference, if significant, would suggest an effect of weld bead location. However, this hypothesis could be dismissed at the outset for two reasons: (a) the NRL study of weld-bead location on another heat of Grade A steel (U-11) discussed above showed no change in NDT temperature with weld-bead location, and (b) the Grade A steels evaluated had uniform microstructures so there would be no metallurgical reason to suspect that the weld-bead location would influence the NDT temperature. In confirmation, subsequent NRL tests of a fourth group of specimens from the U-23 plate welded on the as-rolled surface by NRL showed no difference in NDT temperature from that first established.

GENERALIZED INTERPRETATION OF DT ENERGY

Previous reports [6, 7] have described the structural significance of the curve of DT energy vs temperature for steels, such as shipbuilding steels, which exhibit a micromode fracture transition (i.e., cleavage to dimpled rupture) as a function of temperature. To aid in the understanding of DT results presented here, highlights of DT interpretative procedures are next summarized.

*The ABS grades do not exhibit a variation in microstructure through the thickness as is the case with higher strength, quenched and tempered steels.

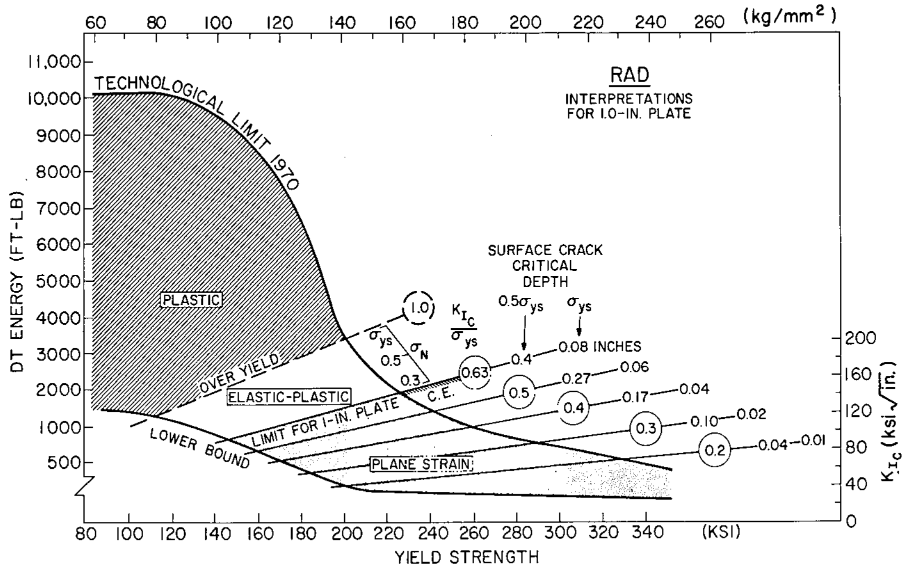

Fig. 4 — The Ratio Analysis Diagram (RAD) for 1-in. plate for engineering interpretation of DT shelf level toughness (Ref.7). The limit for plane-strain behavior L is marked by the K_{Ic}/σ_{ys} ratio, 0.63; the yield criterion YC is marked by the K_{Ic}/σ_{ys} ratio, 1.0. The two ratios bound the elastic-plastic fracture behavior regime as noted.

The DT upper shelf level (fully ductile) is interpreted in terms of structural parameters (i.e., stress and flaw size) by means of the Ratio Analysis Diagram (RAD), Fig. 4 [7]. Material correlations employing linear elastic fracture mechanics (K_{Ic}) tests have enabled lines of constant ratio of K_{Ic}/σ_{ys} to be shown in conjunction with DT energy [8]. The ratio of K_{Ic}/σ_{ys} (or simply "Ratio"), rather than the K_{Ic} value by itself, is proportional to the plasticity or toughness associated with a flawed test piece. Furthermore, in the linear elastic regime, the Ratio lines are proportional to the square root of critical flaw size for a given nominal stress in the flaw vicinity. Flaw sizes corresponding to various Ratios are indicated in Fig. 4.

The Ratio lines on the RAD may be used to distinguish between linear-elastic (plane-strain), elastic-plastic, and fully plastic behavior as a function of thickness. For example, the Ratio that defines the highest plane-strain toughness that can be measured with a given thickness B is computed from the ASTM Committee E-24 criteria as

$$B \geqslant 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \tag{1}$$

The largest Ratio that satisfies Eq. (1) for a given thickness is the limit L ratio. For a 1-in. thickness, this ratio is $0.63\sqrt{\text{in.}}$ as shown on the 1-in. RAD in Fig. 4 Toughness levels above the L ratio indicate elastic-plastic or plastic behavior of the net section. For materials exhibiting an L ratio of toughness, it can be shown that stress levels in excess of 0.3 σ_{ys} cannot be sustained in the presence of through-thickness flaws approximately 3B in length.

A correspondingly larger Ratio approximates the boundary between the elastic-plastic and plastic regions. Based on best estimates currently available, the Ratio for this boundary empirically defines a yield criterion (YC) for the material which denotes the lowest material toughness which permits general through-thickness yielding in the neighborhood of the flaw [9]. In terms of thickness, the YC ratio is computed from the relationship

$$B = 1.0\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 . \tag{2}$$

For a 1-in. thickness, the 1.0 $\sqrt{\text{in.}}$ ratio on the RAD defines the YC. Thus the location on the RAD in terms of DT energy or K_{Ic} and yield stress projects the flawed behavior of the material under the worst conditions of dynamic loading, sharp-tip flaws, and maximum mechanical constraint.

The above concepts demonstrate the straightforward engineering translation of DT shelf energy. However, shipbuilding steels are not often used at temperatures commensurate with upper shelf level behavior but are used at temperatures corresponding to the brittle-to-ductile transition. Consequently, a structural translation of DT energy for the transition temperature regime is necessary.

As with the upper shelf level toughness, concepts of fracture mechanics can be used to interpret the DT energy in the transition region [6]. Because the steels of interest are strain-rate sensitive, fracture mechanics interpretations are based on dynamic toughness K_{Id}. This philosophy is consistent with development of fracture-assurance concepts for ships whose hull materials undergo dynamic loading. Figure 5 presents the general trend of K_{Id} with temperature for a low alloy steel. This curve for A533-B steel was obtained from thick section K_{Id} tests conducted by Westinghouse Research Laboratories [10]. No K_{Id} data for thick sections of shipbuilding steels currently exist from which to define the K_{Id} vs temperature curve for temperatures significantly above the NDT temperature. Other limited K_{Id} data indicate the Fig. 5 trend to be characteristic of such steels. However, it must be emphasized that the shape of the K_{Id} curves for the different grades of shipbuilding steels may vary somewhat from the curve shown.

In Fig. 5 a Ratio scale has been computed from the measured K_{Id} values and the dynamic yield strength (σ_{yd})* at each temperature. Thickness values corresponding to the L and YC ratios may be determined from the Ratio scale and Eqs. (1) and (2). For example, entering the L scale in Fig. 5 at a thickness of 1 in. (i.e., ratio of 0.63 $\sqrt{\text{in.}}$) indicates that

*It has been assumed that the dynamic yield strength may be approximated by an addition of 30 ksi to a static yield strength of 40 to 60 ksi. This yield strength elevation based on studies at NRL represents an average of the yield strength elevation of seven structural steels calculated by Shoemaker and Rolfe [11].

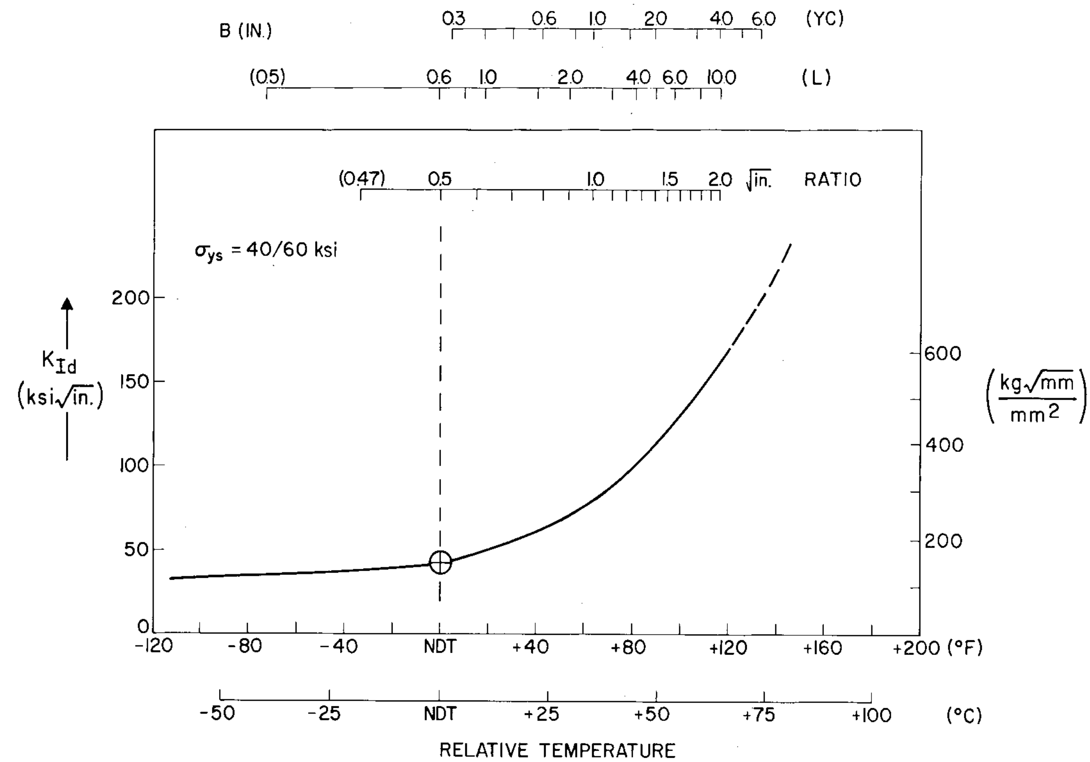

Fig. 5 — The characteristic K_{Id} vs temperature transition curve determined from thick-section dynamic fracture toughness tests. The relationship of the K_{Id} transition curve to the L and YC reference scales is indicated.

plane-strain values for this thickness may be measured at temperatures up to NDT + 20°F (11°C), while for 2-in. thicknesses the plane-strain region extends to NDT + 50°F (28°C). Similarly, a YC condition is exhibited at temperatures in excess of NDT + 60°F (33°C) and NDT + 90°F (50°C) for 1- and 2-in. thicknesses, respectively. It should be noted that the NDT temperature is considered equivalent to a ratio of $0.5\sqrt{\text{in.}}$ This correspondence has been justified on theoretical as well as experimental grounds [12, 13] and is a mean value between the Ratios of $0.4\sqrt{\text{in.}}$ used by Server and Tetelman [14] and $0.63\sqrt{\text{in.}}$ employed by Shoemaker and Rolfe [11] as a correlation with the NDT temperature.

Figure 6 interprets the DT energy vs temperature curve, in terms of the K_{Id} curve of Fig. 5, for a 1-in.-thick shipbuilding steel. Specifically, the NDT temperature, located at the toe of the DT curve, is taken as Ratio $0.5\sqrt{\text{in.}}$. The L index is plotted at the ratio value that satisfies Eq. (1) for the subject thickness (i.e., $0.63\sqrt{\text{in.}}$ for a 1-in. thickness). Finally, the YC index is approximated by the DT midenergy transition temperature. In an engineering context, the midenergy transition is considered to represent the YC criterion for all low strength steels (i.e., less than 100-ksi yield strength) provided the 1-in. DT upper shelf levels are in excess of 4000 ft-lb (500 ft-lb as measured with the 5/8-in. DT specimen). In Ref. 6 examples are presented of the correspondence between the DT midenergy temperature and the temperature at the YC level predicted from the K_{Id} vs temperature curve. It must be remembered that the L and YC temperatures defined schematically for a 1-in. DT curve in

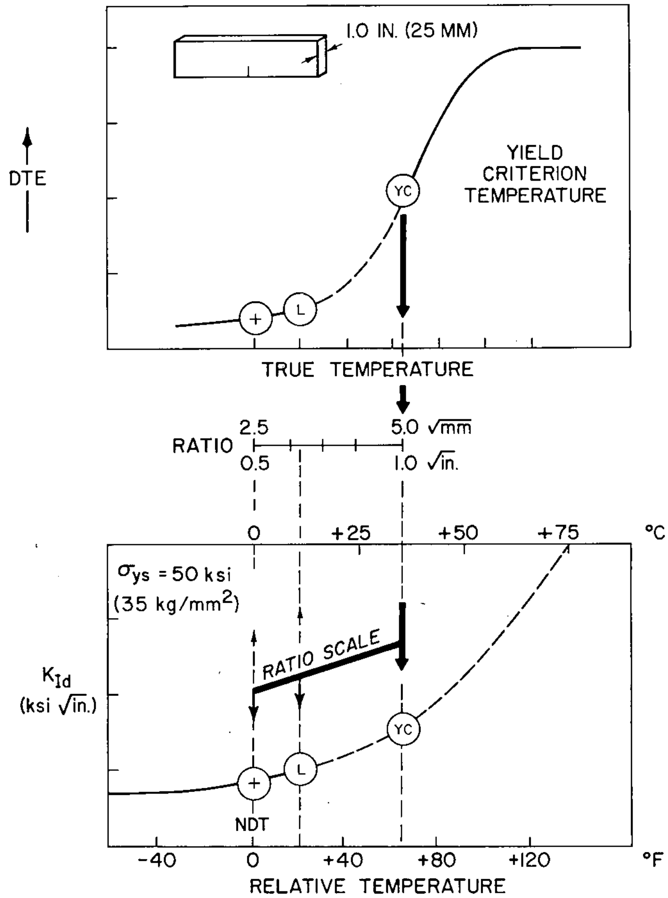

Fig. 6 — Example of toughness indexing procedures based on the DT test for locating the yield criterion as the entry point for the analysis. The midpoint of the DT curve approximates the YC from which the K_{Id} transition curve is indexed. The toughness indexes L and NDT are determined using the ratio scale as indicated.

Fig. 6 apply only for that thickness. These temperatures will be elevated in accordance with Fig. 5 for thicker sections as may be used in ship construction. In other words, the DT test of given thickness establishes an index of metal quality; the effects of mechanical constraint due to increased thickness must be weighed separately.

DT TEST RESULTS

The DT transition curves developed for the shipbuilding steels are compared by grade in Figs. 7—13. The NDT temperature determined from Drop-Weight tests (vertical arrow) in each case corresponds with the toe of the associated DT curve. This trend is consistent with the schematic representation of the DT curve (Fig. 6) since the NDT temperature

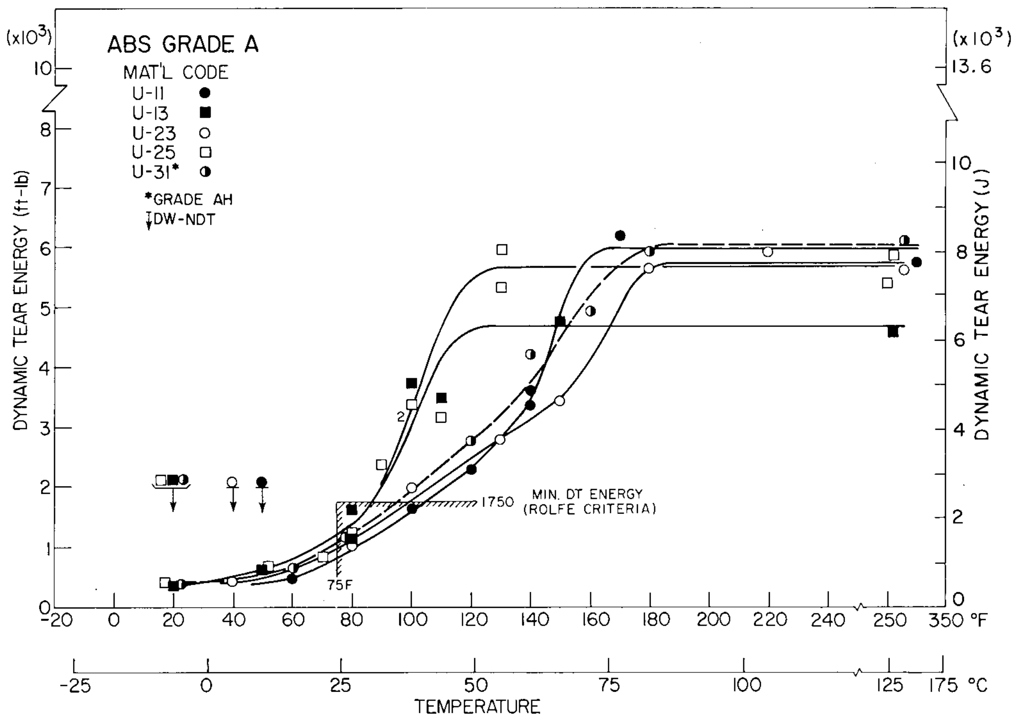

Fig. 7 — Summary of DT test performance of the ABS Grade A plates. The NDT temperature (vertical arrow) corresponds to the toe of the DT curve in each case. Failure of all plates to meet proposed minimum DT toughness requirements (Rolfe criteria) for ordinary-strength hull steel is indicated (1750 ft-lb, 1-in. DT assumed equal to 250 ft-lb, 5/8-in. DT).

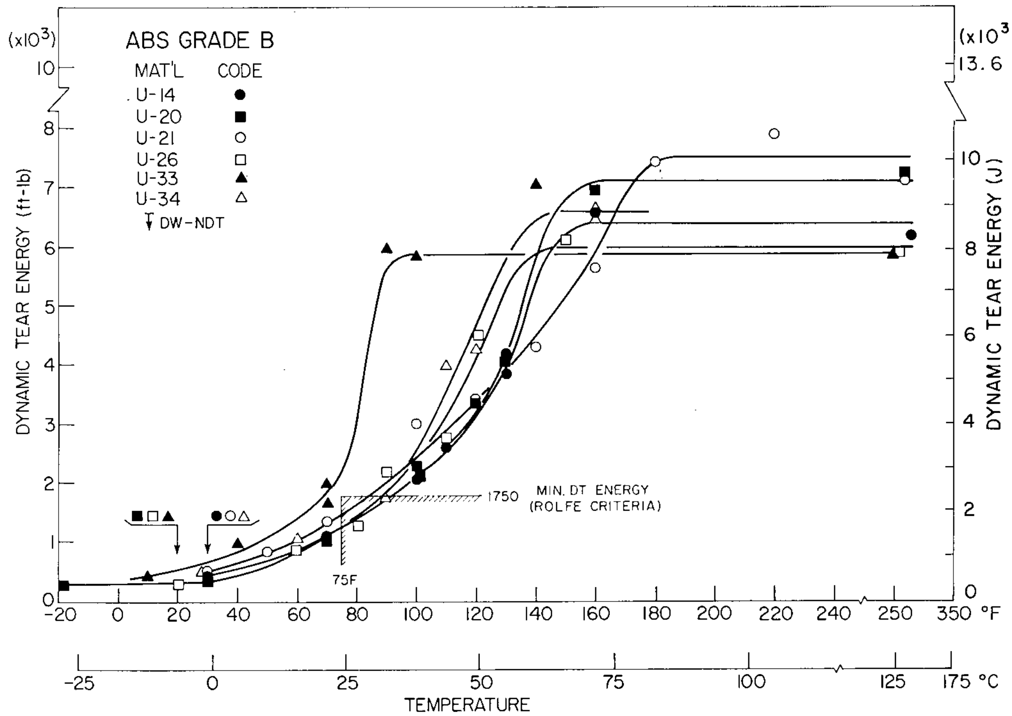

Fig. 8 — Summary of DT test performance of the ABS Grade B plates

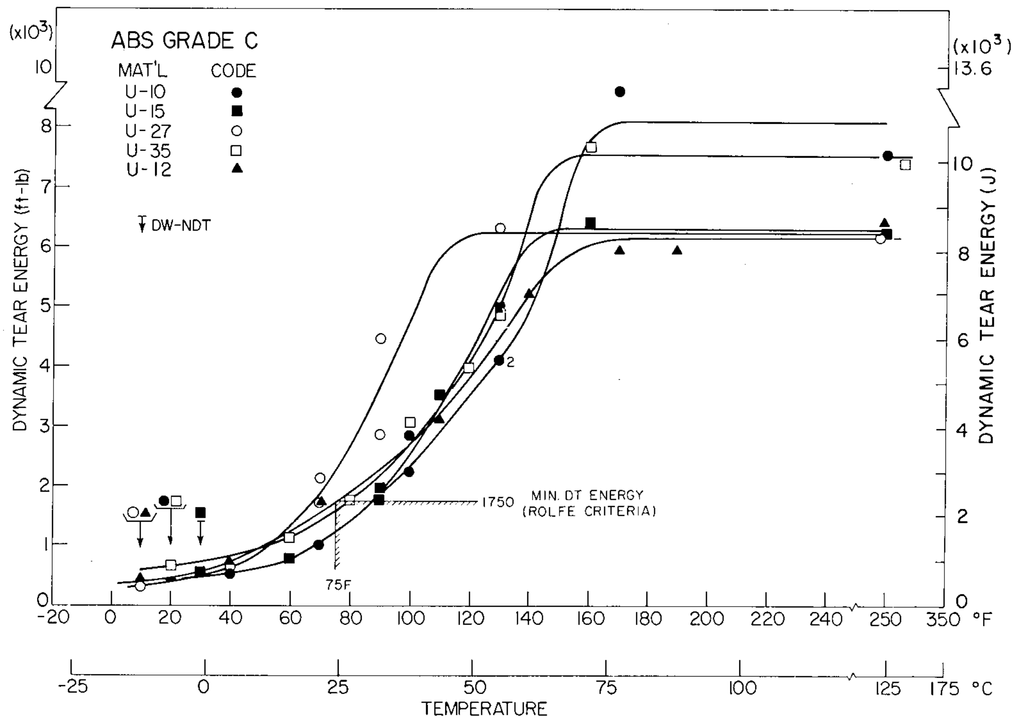

Fig. 9 — Summary of DT test performance of the ABS Grade C plates

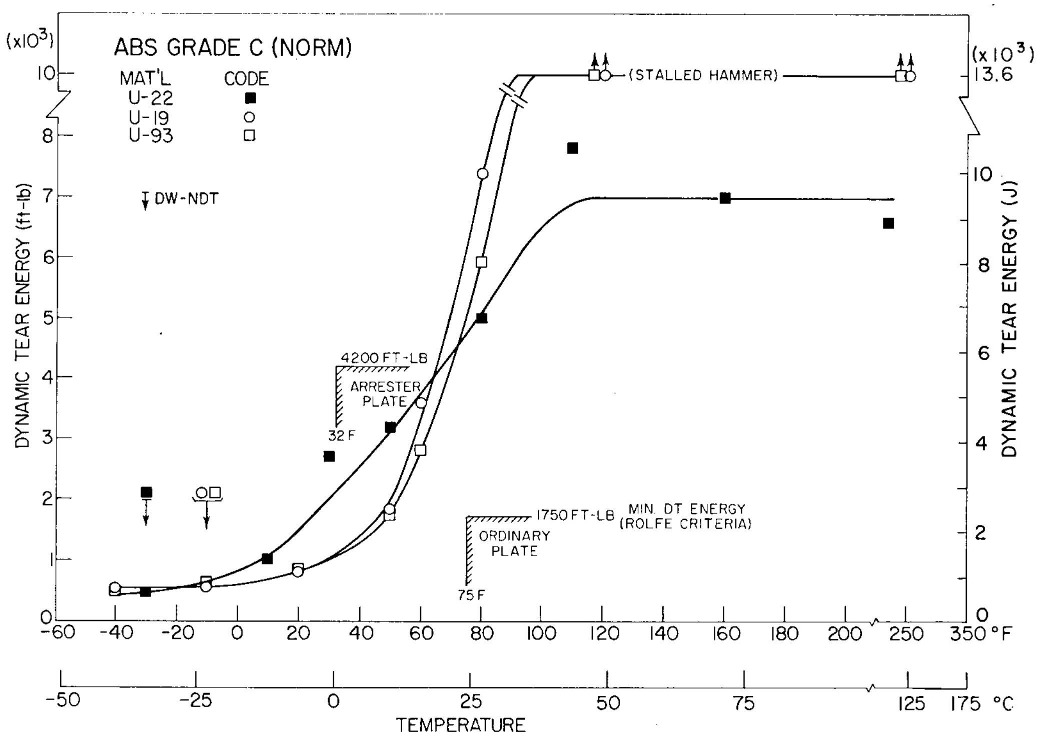

Fig. 10 — Summary of DT test performance of heat-treated (normalized) ABS Grade C plates. Minimum DT toughness requirements proposed for ordinary hull plates and for arrester plates are indicated.

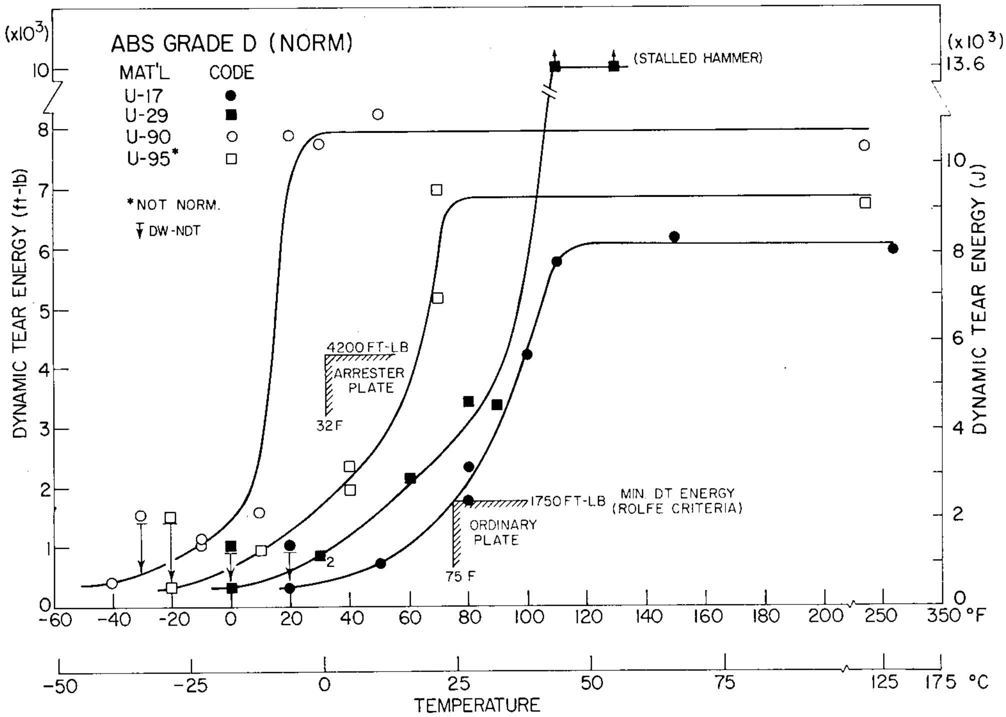

Fig. 11 — Summary of DT test performance of heat treated (normalized) ABS Grade D plates and of one as-rolled ABS Grade D plate.

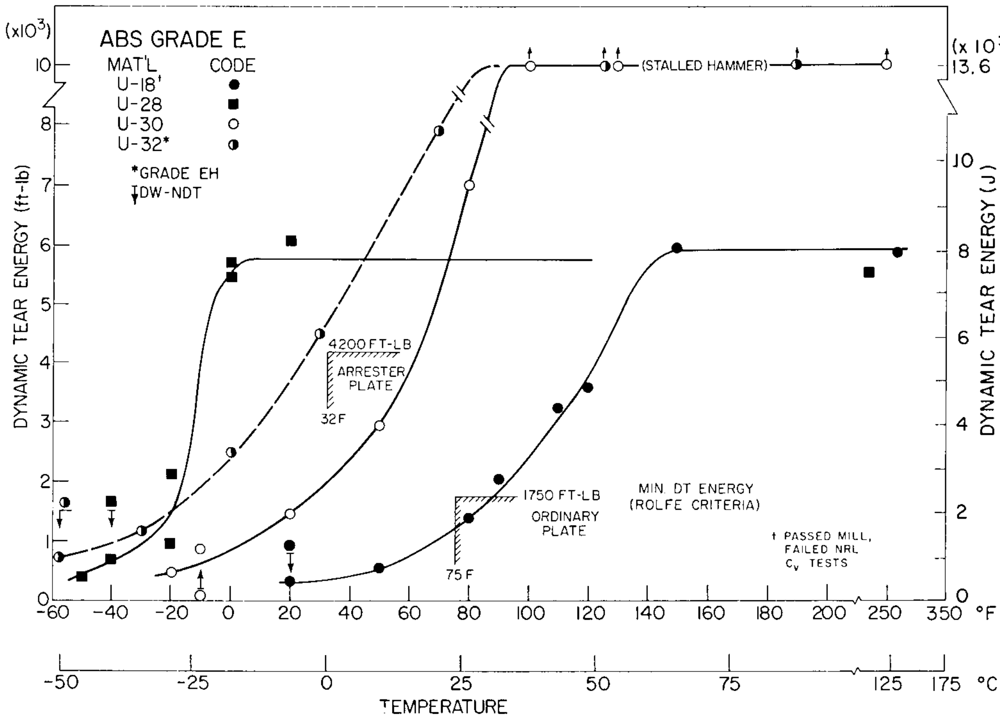

Fig. 12 — Summary of DT test performance of ABS Grade E plates (Grade E specification requires normalization heat treatment.)

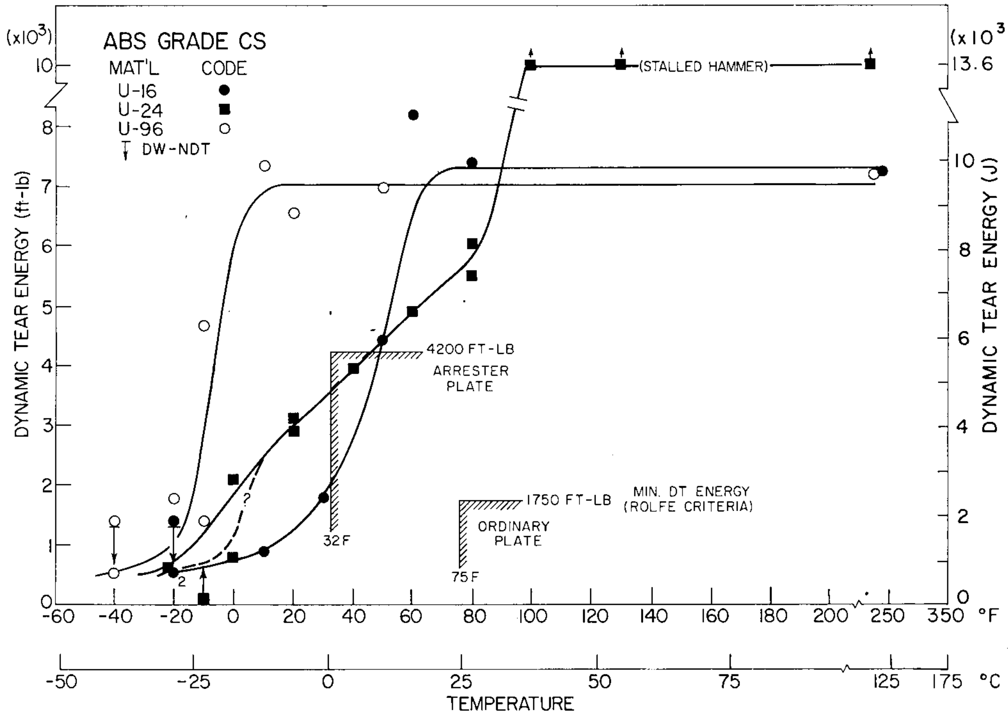

Fig. 13 — Summary of DT test performance of ABS Grade CS plates (Grade CS specification requires normalization heat treatment.)

physically denotes the beginning of the temperature region of sharply increasing notch toughness (DT energy) with temperature. Accordingly, the DT curves substantiate the validity of the NDT performance patterns discussed above.

In most cases the 1-in. DT upper shelf energy values exceed 6000 ft-lb considered equivalent to 750 ft-lb, 5/8-in. DT energy as discussed later (Table 2). This upper shelf energy level, as seen from the RAD (Fig. 4), denotes a high level of toughness for the "plastic" regime. In cases where the plate (and specimen) thickness is somewhat thicker or thinner than the nominal 1 in. thickness, the shelf energy equivalent for a 1-in. DT specimen can be computed from the relationship [15]*

$$E = R_p \, \Delta a^2 B^{1/2}, \tag{3}$$

where E is DT energy (ft-lb), R_p is a material constant, Δa is the original unbroken ligament (3 in.), and B is the specimen thickness (in.). Since the thickness term appears to the one-half power, energy corrections due to the small thickness variations encountered are negligible. Note from Figs. 7—13 that the temperature region for shelf level behavior is on the order of 120° F to 180° F for most Grade A, B, and C plates; shelf temperatures are lower for the normalized plates (C-norm, D-norm, CS, and E), and the spread is larger (0° to 120° F). It is apparent from these data that ordinary shipbuilding steels typically will not exhibit shelf level behavior at any temperature of normal operation. This general characteristic is not necessarily detrimental to the application of these steels since the high toughness levels associated with upper shelf temperatures may not be required for satisfactory behavior in ship structures.

Most of the materials exhibit a YC index (DT midenergy transition) at temperatures 70° to 110° F above the NDT temperature (Fig. 14). In terms of absolute temperature, the YC indexes of the as-rolled plates (Grades A, B, and C) generally lie between 80° and 135° F (Fig. 15). For the heat-treated plates (Grades C-norm, D-norm, E, and CS) the YC index temperatures show a larger variation (i.e., —15° to 95° F) but, for the most part, lie below the range for as-rolled grades.

The results suggest that, in general, none of the ordinary hull steels will consistently exhibit a YC level of toughness at the minimum service temperature. It follows that these steels will be in the elastic-plastic toughness regime in service. Nonetheless, it is believed that fracture-safe performance can be achieved with these steels through application of knowledgeable ship design practices that restrict plastic deformation and by the inclusion of crack arresters that limit the extent of a fracture.

When the DT curves from all grades are considered together, it is apparent that little difference exists among the as-rolled grades (A, B, and C). Further, a considerable improvement in toughness is found with heat treatment. Of the heat-treated grades, Grades E and CS are clearly the best. Unfortunately, the preliminary data reported here indicate a large

*A least-squares fit of the data forming the basis for this equation results in exponents of 1.8 and 0.7 for the factors a and B, respectively. Equation (3) also fits the data reasonably well and is set forth for computational ease.

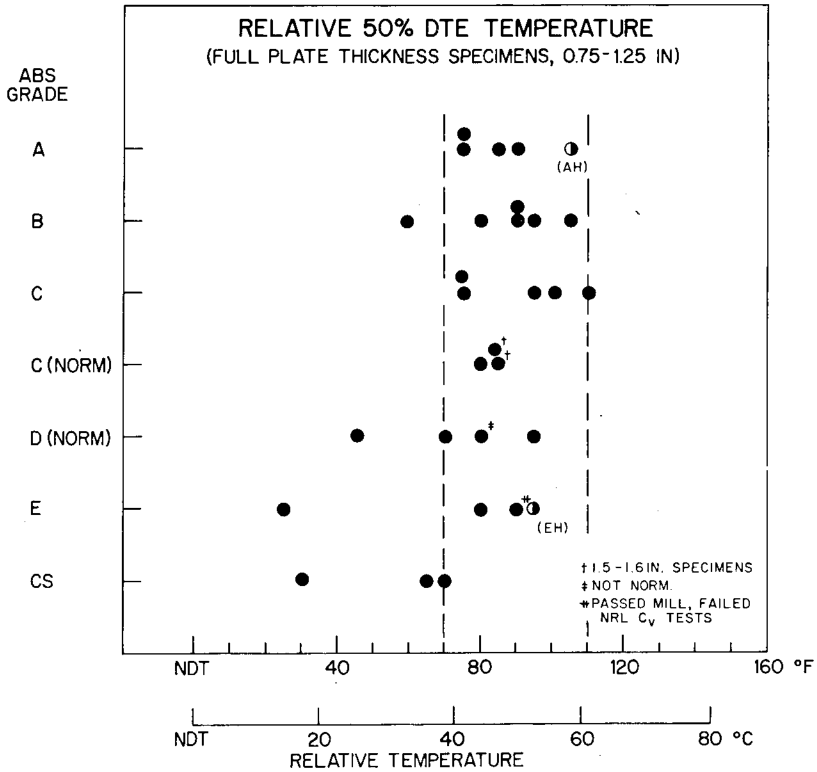

Fig. 14 — DT midenergy transition temperatures relative to the NDT temperatures. With few exceptions, the midenergy transition lies in the temperature range NDT + 70° F to NDT + 110° F. The midenergy transition indexes the yield criterion.

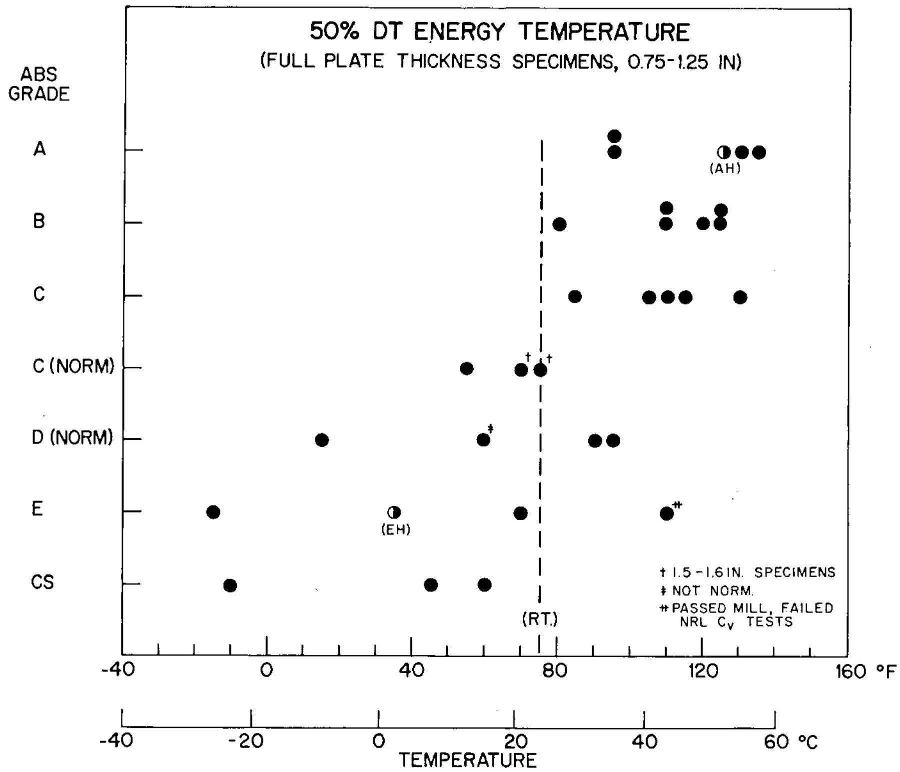

Fig. 15 — Summary of DT midenergy transition temperatures determined for the test plates. Superior performance by ABS Grades E and CS is suggested by the data.

temperature variation in the brittle-ductile transition for the normalized plates. Consequently, the specification of normalization by itself cannot assure a consistent level of toughness at the minimum ship service temperature. For example, the normalized plates in Figs. 10—13 having NDT temperatures of 0°F or less exhibit an order of magnitude variation in DT energy at 30°F i.e., from 900 to 7930 ft-lb (Table 4).

CHARPY-V RESULTS

The C_v results for selected plates are compared to the DT performance in Figs. 16—22; curve features are summarized in Table 2. Plates from Grades A, C, and E were selected for testing on the basis of the highest and lowest NDT temperatures for a given grade. Since all the Grade B plates had comparable NDT temperatures, plate selection for this grade was on the basis of high and low values of Mn/C ratio. Only one plate each of Grades C-norm, D, and CS was characterized.

The results indicate a lack of correlation of C_v energy with either the NDT temperature or with a given DT energy in the DT transition regime. The variation in C_v energy is large not only among the different grades but also among the plates within a given grade. Consider the following examples:

- The non-heat-treated grades exhibited a C_v energy variation at the NDT temperature of 13 to 44 ft-lb.

- The normalized grades exhibited an order of magnitude variation in C_v energy at the NDT temperature, extending from about 20 to 200 ft-lb.

- Heat-to-heat differences in plates of Grade E resulted in a variation in average C_v energy at the NDT temperature of about 60 ft-lb.

It is evident that such variations preclude the establishment of a meaningful C_v "fix" energy level with which to approximate the NDT temperature in the absence of Drop-Weight tests.

By comparison, differences in DT energy at the NDT temperature were small for all the grades, i.e., only about 5% of the DT upper shelf energy. In Table 2 NDT temperatures are shown to correspond to a 1-in. DT energy of 300 to 600 ft-lb. It follows that, unlike C_v results, DT determinations by themselves can be used to approximately fix the NDT temperature in the absence of Drop-Weight tests. Moreover, it is apparent that an empirical correlation of C_v and DT energy in the transition region is not likely.

It was noted above that Grades D and E include C_v energy as part of their material specifications (35 ft-lb at 32°F for Grade D and 45 ft-lb at 14°F for Grade E). From the scatter in the C_v data observed here, it is evident that it would be most difficult to relate the C_v specifications to structural performance at the service temperature. The specification of minimum C_v values for Grades D and E, however, may be useful as a means of insuring consistent quality steel once the possible variation in C_v energy level is known. The significance of the inferred quality level, then, must be judged from past experience with the steel grade.

Table 4
DT Energy of Test Plates at 75°F (24°C) and at 32°F (0°C)
[1-in. DT specimen thickness (nominal)*]

Material Type	Plate (Code)	Thickness (in.)	NDT (°F)	NDT (°C)	DT Energy (ft-lb)† at 75°F (24°C)	DT Energy (ft-lb)† at 32°F (0°C)	Rolfe DT Criteria ‖ [1750 ft-lb‡ at 75°F (24°C)]
ABS-A	U-11¶	2.0	50	10	830	~400	F (FAIL)
	U-13	0.75	20	−7	1200**	450**	F
	U-23	1.0	40	4	970	400	F
	U-25	0.8	20	−7	1100**	450**	F
(AH)	U-31	1.0	20	−7	1100	450	F
ABS-B	U-14	1.0	30	−1	1250	450	F
	U-20	1.0	20	−7	1250	350	F
	U-21	1.0	30	−1	1470	550	F
	U-26	0.88	20	−7	1250**	350**	F
	U-33	1.0	20	−7	2200	700	P (PASS)††
	U-34	1.0	30	−1	1300	490	F
ABS-C	U-10	1.0	20	−7	1200	500	F
	U-15	1.0	30	−1	1200	570	F
	U-27	1.0	10	−12	2250	500	P††
	U-35	1.25	20	−7	1600**	750**	F
	U-12	1.0	10	−12	1720	600	F
ABS-C (Normalized)	U-22	1.0	−30	−34	4700	2100	P
	U-19	1.5	−10	−23	6200**	1100**	P
	U-93	1.63	−10	−23	5000**	1100**	P
ABS-D (Normalized)	U-17	1.0	20	−7	1750	400	F
	U-29	1.0	0	−18	2770	900	P
	U-90	1.0	−30	−34	7930	7930	P
	U-95‡‡	1.0	−20	−29	6840	1800	P
ABS-E	U-18	1.0	20	−7	1240	370	F
	U-28	0.75	−40	−40	5750**	5750**	P
	U-30	1.0	−10	−23	6100	1970	P
(EH)	U-32	1.0	−60	−51	8400	4700	P
ABS-CS	U-16	1.0	−20	−29	7300	1970	P
	U-24	1.0	−10	−23	5600	3550	P
	U-96	1.0	−40	−40	7000	7000	P

* 1-in. DT specimen unless noted.
† Multiply by 1.36 to obtain joules, J.
‡ Assumed equal to 250 ft-lb, 5/8-in. DT energy.
‖ Ordinary hull plate.
¶ DT specimen (1-in. thick) contained one plate surface.
** DT specimen thickness equal to plate thickness.
†† Fails Rolfe NDT criteria.
‡‡ Not normalized.

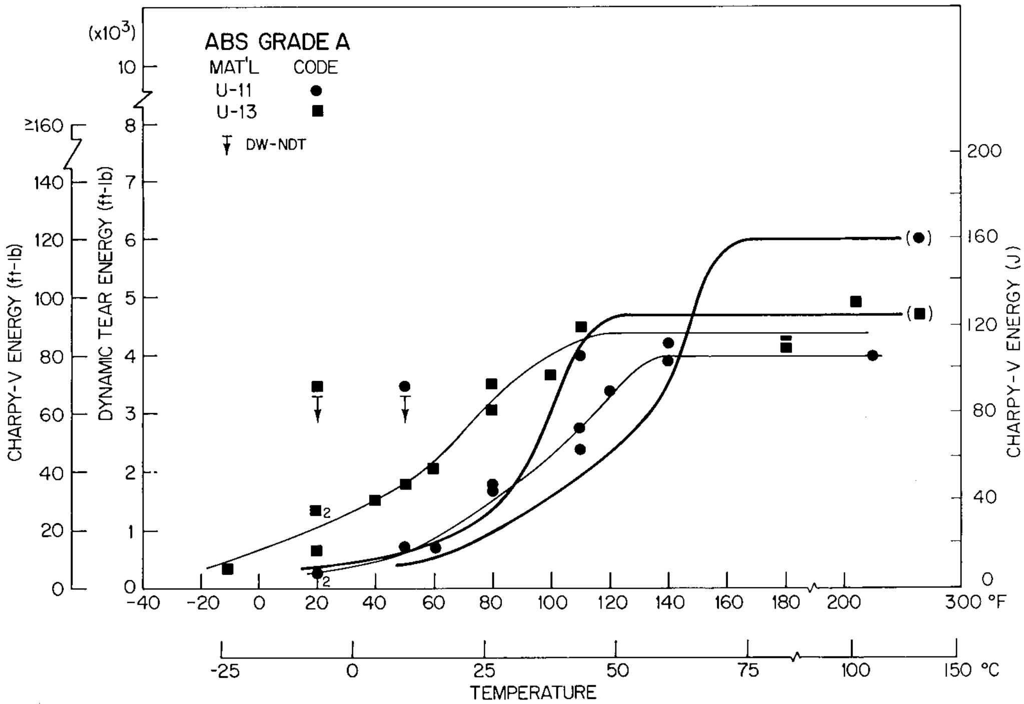

Fig. 16 — Charpy-V performance of two ABS Grade A plates exhibiting high and low NDT performance. Heavy curves reference the DT performance of the plates shown in Fig. 7. Symbols in parentheses identify individual DT curves in Figs. 16-22 and are not specific DT data points.

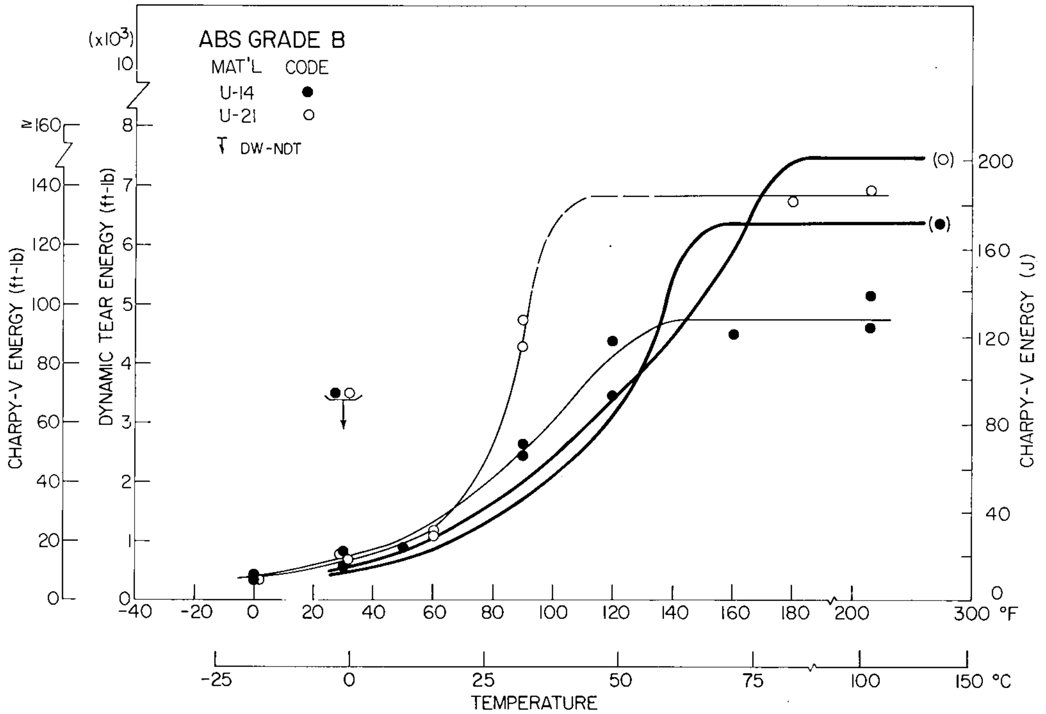

Fig. 17 — Charpy-V performance of two ABS Grade B plates, U-14 and U-22, having high and low C/Mn ratios, respectively

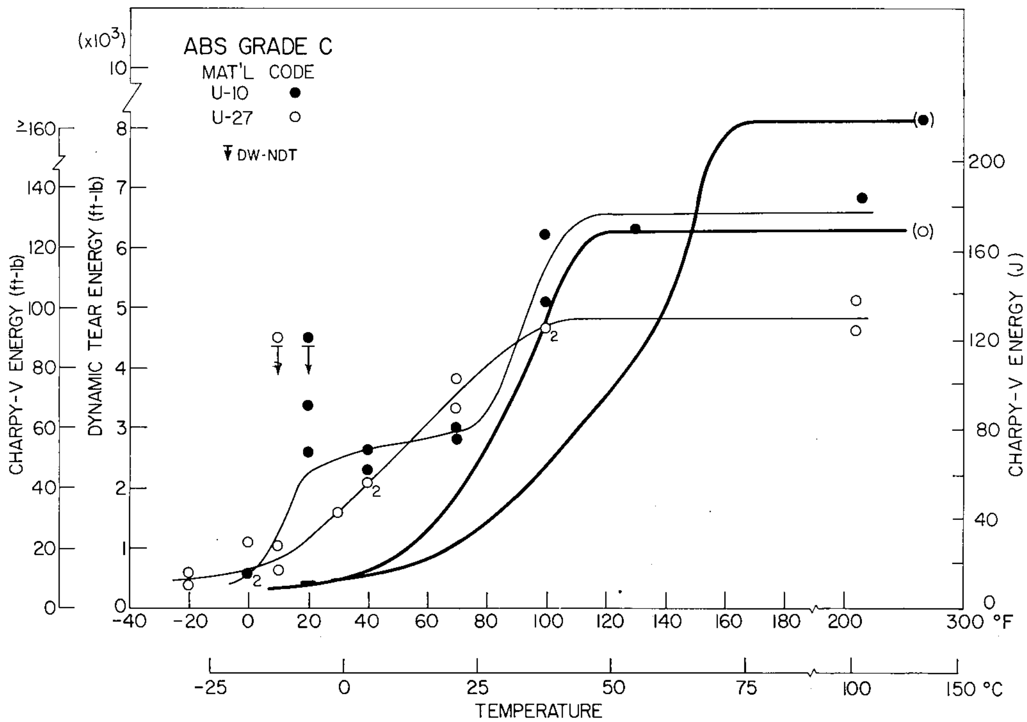

Fig. 18 — Charpy-V performance of two ABS Grade C plates

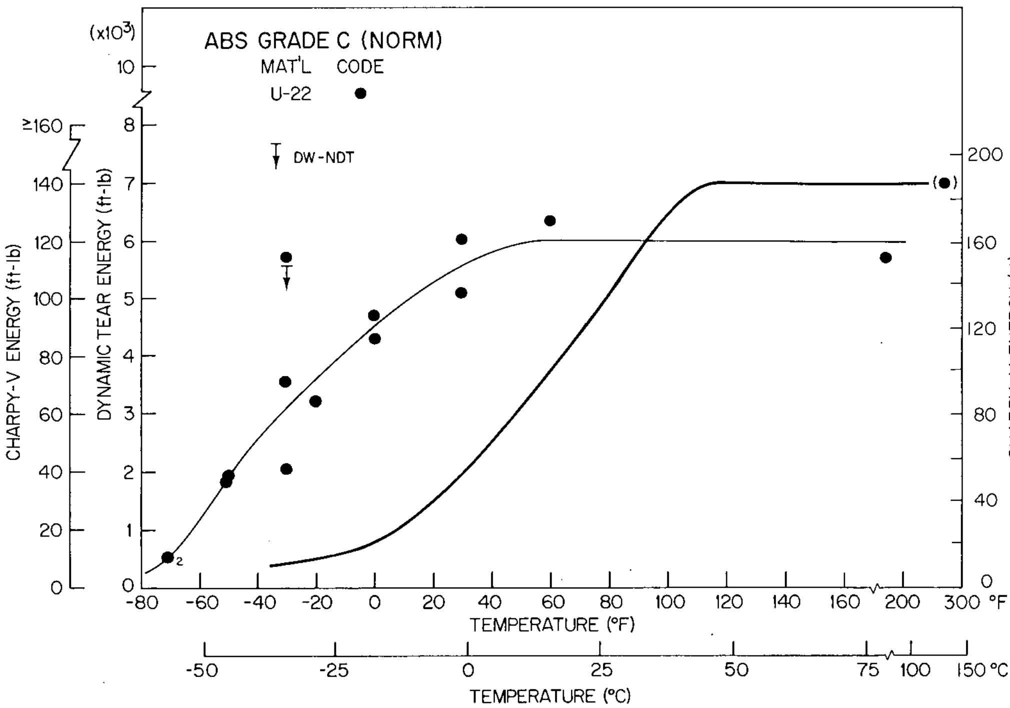

Fig. 19 — Charpy-V performance of a heat-treated (normalized) ABS Grade C plate

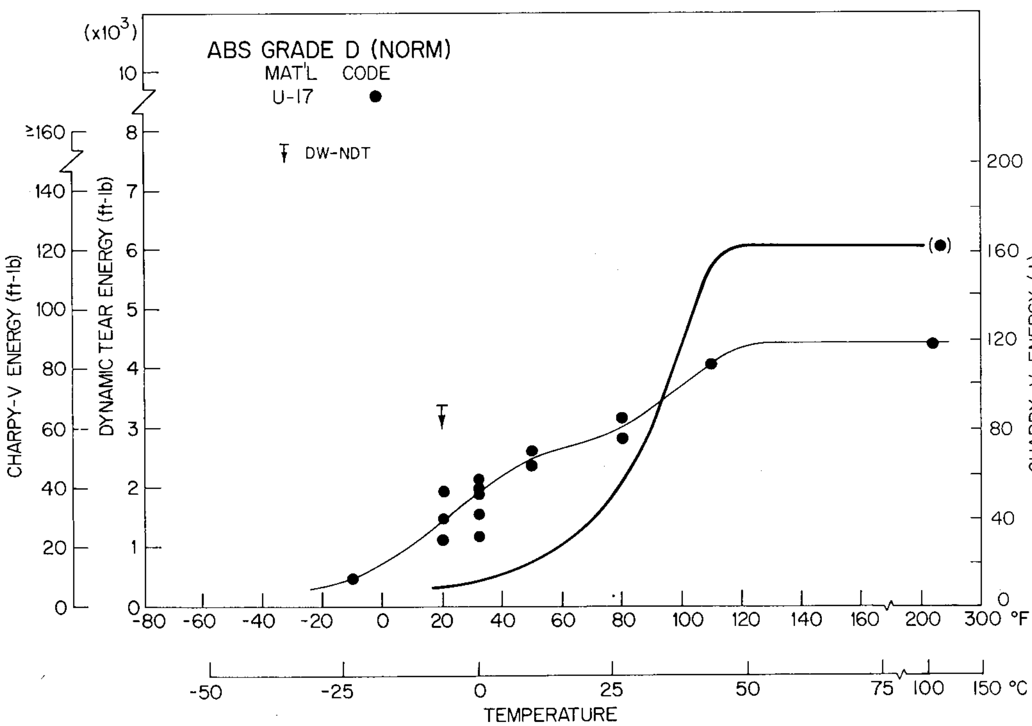

Fig. 20 — Charpy-V performance of a heat-treated (normalized) ABS Grade D plate

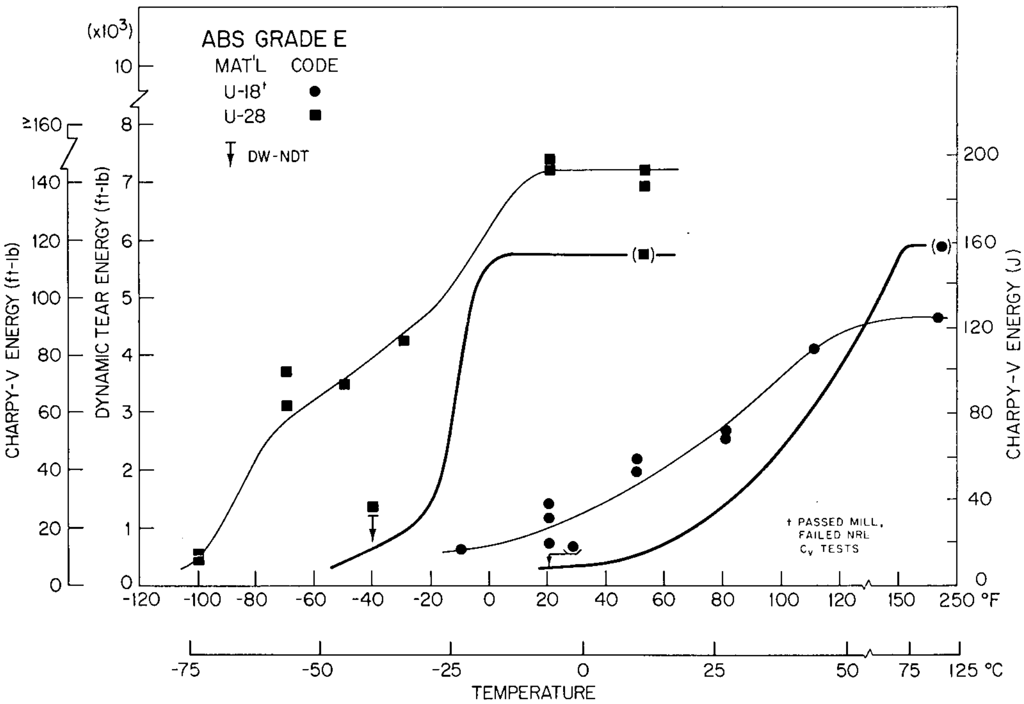

Fig. 21 — Charpy-V performance of two ABS Grade E plates exhibiting high and low drop-weight NDT performance. Plate U-18 passed mill C_v tests but failed NRL C_v tests for Grade E certification.

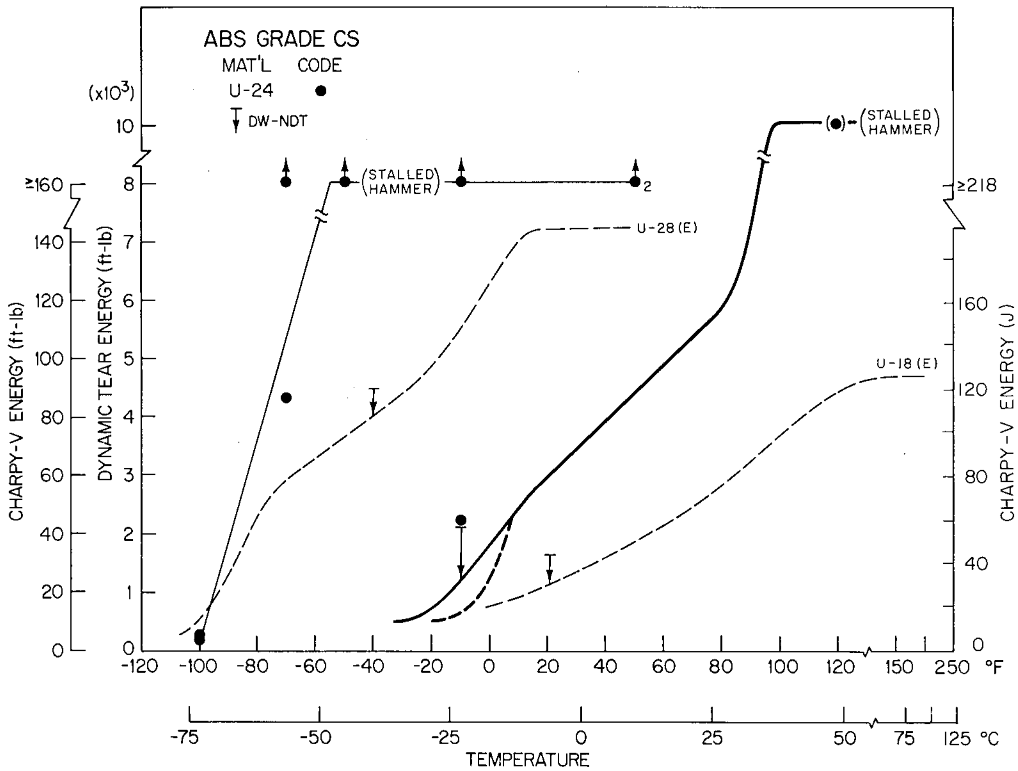

Fig. 22 — Charpy-V performance of one ABS Grade CS plate. Charpy-V curves for two ABS Grade E plates are also shown from Fig. 19. Note the order of magnitude difference in average C_V energy at NDT among the three plates.

GRADE AH AND EH ASSESSMENTS

An investigation of the H grades (higher yield strength) was not included in the original program scope; however, an exploratory investigation was conducted with one plate each of Grades AH and EH. As seen from Table 2, the plates exhibited a yield strength approximately 20 to 30% higher than that of ordinary Grade A and E plates. The DT curves determined for the Grade AH and EH plates have been included in Figs. 7 and 12, respectively (dashed curves). It can be seen that the toughness transitions for these plates are within the scatterbands for their lower strength counterparts. In the case of the Grade AH plate, its DT transition curve follows closely the curves for two Grade A plates. Its NDT temperature is some 20°F to 30°F lower than the NDT temperatures of these plates but within the range of NDT temperature of all Grade A plates. The YC index temperature for the Grade AH plate lies at NDT + 105°F, or slightly higher than the range NDT + 75°F to 90°F found for the YC index of the Grade A plates (Fig. 14). The Grade EH plate exhibits a somewhat lower NDT temperature than the Grade E plates; however, its DT curve falls within the DT curve distribution for Grade E. The YC temperature relative to NDT is NDT + 100°F, comparable to the high end of the range observed for Grade E.

Overall, no major difference in NDT or DT performance by H-grade plates was indicated by the limited evaluations.

RELATIONSHIP OF MEASURED NOTCH TOUGHNESS TRENDS TO RECOMMENDED FRACTURE CONTROL GUIDELINES

As discussed, fracture control guidelines for welded ship hulls have been recommended by Rolfe and coworkers (1). Prior to implementing these guidelines it was necessary to ascertain the ability of current shipbuilding steels to meet the proposed criteria. Basically, a minimum toughness level of $K_{Id}/\sigma_{yd} = 0.9\sqrt{\text{in.}}$ at the minimum service temperature (32°F, 0°C) has been recommended. Since this toughness exceeds that which can be determined with Eq. (1) using linear elastic fracture mechanics specimens of 1-in. thickness, other toughness criteria based on Drop Weight and DT tests have been proposed. This proposed level of toughness is not intended, nor sufficient, to guarantee a complete absence of brittle fracture but is set forth as reasonable for economic reasons. A fail-safe philosophy nevertheless is intended through the use of crack arresters that limit the extent of brittle fractures.

NDT Criterion

A minimum NDT temperature of 0°F has been proposed to give assurance that the toughness transition from brittle to ductile behavior begins at a temperature below the minimum service temperature. To compare the actual materials performance with this criterion, the NDT data evolved in the present study are considered to represent average values. However, a final specification of mean NDT temperatures must be based on a strict statistical analysis involving many more heats than were evaluated here. The NDT trends evolved in the present study suggest that there will be a high rejection rate of as-rolled plates, Grades A, B, and C, when tested against a 0°F NDT criterion. If the observed trends are verified through further statistical sampling, it is readily apparent that ship construction in accordance with the proposed criterion will gravitate to the use of only normalized plates for important (critical) strength members.

Toughness At Minimum Service Temperature

For the case of a 0°F NDT temperature, Rolfe and coworkers estimate the toughness at 32°F to be $K_{Id}/\sigma_{yd} = 0.9\sqrt{\text{in.}}$ However, existing data are insufficient to define K_{Id} trends exactly for shipbuilding steels. This area requires further investigation before it will be possible to state with certainty that a Ratio of $0.9\sqrt{\text{in.}}$ or higher will be attained at NDT + 32°F. The K_{Id} curve in Fig. 5, for example, indicates that this value will not be attained at temperatures below NDT + 55°F for material exhibiting plane-strain constraint. Also of interest here is the authors' estimate of an NDT "equivalence" Ratio, $0.5\sqrt{\text{in.}}$, compared with Rolfe's estimate [1] of $0.6\sqrt{\text{in.}}$. It is felt that this difference is academic and that the toughness at NDT cannot be established using an engineering test procedure to within $0.1\sqrt{\text{in.}}$ ratio value.

The K_{Id} curve of Fig. 5 suggests that a ratio lower than $0.9\sqrt{\text{in.}}$ (i.e., $0.75\sqrt{\text{in.}}$) may be exhibited by some steels at NDT + 32°F. With this level of toughness, plates of 1.4-in. thickness will exhibit plane-strain behavior (Eq. (1)) and surface flaws on the order of 0.2-in. deep will be critical stress loading. At one-quarter yield-stress loading a critical flaw length for a through-thickness flaw in a tension plate of this toughness level would be approximately 6 in..* Flaw sizes of this magnitude are not uncommon in cargo ships. Thus, it is readily apparent that higher toughness levels would be required of hull steels to assure a complete absence of running cracks. It follows that K_{Id} vs temperature curves should be established for the steels of interest.

The DT trends determined in this study suggest caution in associating a given Ratio with a fixed temperature increment above the NDT temperature. For example, the K_{Id} curve of Fig. 5 locates the YC index of a 1-in. plate (equivalent to a ratio of $1.0\sqrt{\text{in.}}$) at NDT + 60°F. On the other hand, for a large number of the shipbuilding steels examined, the YC index was attained only at temperatures in excess of NDT + 70°F to 110°F. This trend and the K_{Id} curve both suggest that the Ratio requirement of $0.9\sqrt{\text{in.}}$ (since it is close to the YC ratio of $1.0\sqrt{\text{in.}}$) may not be achieved at the minimum service temperature, 32°F (0°C), for the ordinary-strength shipbuilding steels, except for some plates of the Grades E and CS. Additional research is required to ascertain the conservatisms in the YC index as defined by NRL. Hopefully, it will be found that the toughness corresponding to the DT midenergy level actually exceeds a ratio of $1.0\sqrt{\text{in.}}$. This would imply that a $0.9\sqrt{\text{in.}}$ ratio toughness would be attained at temperatures closer to the NDT temperature than to NDT + 70° to 110°F.

* These calculations assume plane-strain behavior, i.e., that the thickness satisfies Eq. (1). For smaller thicknesses, valid K_{Id} values cannot be established using current techniques. The resulting lack of thickness-induced constraint may lead to elastic-plastic behavior. For this case, a higher effective toughness is exhibited and flaw size calculations, such as those above, can lead to quite conservative estimates.

DT Energy Criteria

Rolfe's proposed toughness criteria include minimum 5/8-in. DT energy requirements at 75°F (24°C) for ordinary-strength hull plates and at 32°F (0°C) for crack arrester materials. The 75°F (24°C) test temperature rather than the minimum service temperature of 32°F (0°C) was chosen for the hull plates because it would be difficult to establish a significant increase in DT energy between the 0°F NDT temperature, where the DT energy is low by definition, and the 32°F service temperature. Tables of increasing DT energy requirements for hull materials and arrester materials, as a function of increasing yield strength, are provided in Ref. 1. Considering a 40-ksi static yield strength material, which is representative of the majority of plates described here, the 5/8-in. DT requirement is 250 ft-lb for ordinary-strength hull plates and 600 ft-lb for arrester materials. To compare the present results with these minimum values, an approximate relationship between 5/8-in. and 1-in. DT energy values, noted below, is available.

At the time this program was initiated, the recommendation of 5/8-in. DT energy values had not yet been made and this size specimen* was not included in the program scope. However, it is expected that follow-on studies, using the 5/8-in. DT specimens cut from the same plates characterized here, will be undertaken by the ABS laboratory. NRL has demonstrated [3] that the proportionality factor between upper shelf energies obtained with 1-in. and 5/8-in. DT specimens is 8:1. In the transition temperature region, the proportionality factor appears to be somewhat less than 8:1. Insufficient comparisons have been made to permit an exact determination in this region; however, preliminary data suggest that a factor of 7 provides a good data fit and that a factor of 8, as defined for the upper shelf correspondence, is also reasonable for the transition temperature region. For the present analysis, the 250 ft-lb 5/8-in. DT criterion will be considered equivalent to 1750-ft-lb 1-in. DT energy. Similarly, the 600 ft-lb 5/8-in. DT requirement for arrester material will be considered equal to 4200 ft-lb 1-in. DT energy.

The 1-in. DT values, equivalent to the above 5/8-in. DT criteria, are compared in Figs. 7—13 with the DT trends of both the as-rolled and normalized grades; a summary is presented in Table 4. These comparisons lead to the following conclusions:

- For ordinary-strength hull plates, it is predicted that the as-rolled grades (A, B, C) generally will not meet a 5/8-in. DT requirement of 250 ft-lb at 75°F (assumed equal to 1750 ft-lb 1-in. DT energy).

- For the normalized grades (C-norm, D-norm, E, and CS) it is concluded that a 250 ft-lb requirement at 75°F can be met in most cases.

- A 5/8-in. DT requirement of 600 ft-lb at 32°F (4200 ft-lb 1-in. DT energy) for arrester materials of 40-ksi yield strength will not be met by a majority of the ordinary-strength hull grades. For example, the data show only some of Grades E and CS plates

* The 5/8-in.-thick DT specimen has planar deminsions of 1 5/8 in. (width) × 7.0 in. (length) and features a 0.5-in.-deep machined notch (sharpened by knife-edge technique).

offering 1-in. DT energies above 4200 ft-lb at 32°F. A significant rejection rate for arrester material produced to either of these grades probably would be exhibited. Of the Grade C-norm and Grade D-norm plates, only one plate met the requirement for arrester material.

Finally, it is observed from Table 4 that all of the steels which met the proposed 0°F NDT requirement also satisfied the (1-in. equivalent) DT energy requirement at 75°F. The converse, however, is not true; some plates (e.g., U-33, Grade B and U-17, Grade D) exhibited an NDT temperature above 0°F but still satisfied the DT toughness requirement at 75°F. From these variations in shape of the DT curves it can be concluded that the development of toughness between 0°F and 75°F is not a unique function. Further research is required to establish the resultant variation in DT energy and in Ratio value at 32°F when the proposed criteria at 0°F and 75°F have been met.

RECOMMENDATIONS FOR FOLLOW-ON RESEARCH

Crack Arrester Materials

Steels used as crack arresters must, by definition, exhibit a high level of toughness. This requirement could be interpreted to mean upper shelf behavior at the minimum service temperature. From the DT trends exhibited by each of the ordinary-strength hull grades investigated here, it can be inferred that (a) the non-heat-treated plates exhibit insufficient toughness at a minimum service temperature of 32°F (0°C) to be used as crack arresters, and (b) the heat-treated plates at 32°F (0°C) will be in the middle to lower third of their DT transition regime on the average and will not consistently offer upper shelf toughness protection. These steels at or below the toughness level associated with YC performance will, when subjected to a certain degree of plastic deformation within the transition regime, exhibit a partial cleavage (brittle) mode of fracture. The possibility exists, therefore, that a crack arrester satisfying the above requirements could fail in a brittle manner after sustaining a certain amount of plastic deformation if this deformation is insufficient to absorb the energy released by a fracture originating in a brittle hull plate.

Past experience with ship fractures and with crack arrest tests, such as the Robertson test, indicates that arrest will occur at toughness levels less than upper shelf toughness for normal plate loading levels. On the basis of those results, a YC level of toughness has been deemed sufficient for crack arrest. Certainly, the toughness requirements for arrester material, as proposed by Rolfe, will lead to a YC performance level. On the other hand, knowing that arrester material can exhibit unstable fracture following plastic deformation implies that crack arrest, a priori, cannot be guaranteed solely by an energy criterion unless upper shelf level behavior is, in fact, also required.

Crack arrest behavior appears to be related to the driving force available from the structure which, in turn, is related to the configuration of the structure in the neighborhood of the fracture. On the basis of this hypothesis it is possible that a future requirement of different toughness levels for arresters may be necessary for different types of ships. The supertanker, for example, can subject the hull to significant lateral bending stresses which are of second-order importance in smaller ships. It is recommended that structural tests be conducted to simulate the driving forces associated with different ship designs on postulated brittle cracks in hull plates. Such tests would allow positive conclusions to be reached concerning proper arrester toughness requirements for individual service conditions.

Thickness Effects

It is known that the mechanical constraint associated with increasing thickness inhibits plastic flow in the neighborhood of a flaw. This phenomenon serves to decrease the fracture toughness of thick sections in comparison with thin sections at a given temperature within the transition region. In effect, increased thickness elevates the temperature regime of applicability of linear elastic fracture mechanics. At sufficiently high temperatures, nonetheless, the metallurgical micromode transition (cleavage to dimpled rupture) overshadows the effects of mechanical constraint and a "constraint transition" to high toughness evolves, just as for thin sections.

This report has considered primarily the toughness trends exhibited by steels of 1 in. thickness. It is recommended that both a DT and K_{Id} specimen testing program be undertaken to define toughness trends with thicknesses in excess of 1 in. as they may be used in ship construction. From past experience with other steels one would expect a constraint elevation of the YC temperature on the order of 25° to 40°F (14° to 22°C) for thicknesses on the order of 2 in.. While this temperature increment is not large, it nevertheless is felt to be significant. Specifically, a 25° to 40°F constraint elevation is noted to be of the same order of magnitude as the 32°F temperature increment above the NDT temperature for which the recommended toughness criteria [1] stipulate the evolution of sufficient toughness for fracture-safe operation. The suggested research program would establish what, if any, upward adjustment in the proposed DT energy levels is required for hull plates and arrester materials thicker than 1 in.. Also, full-thickness DT tests are of interest to assess possible metallurgical changes affecting toughness in thicknesses exceeding 1 in..

Metallurgical Effects

It is apparent from the toughness characterizations evolved in the subject program that the currently produced grades of ordinary-strength hull steels do not consistently exhibit sufficient toughness to sustain any but the smallest flaws (several inches) for quarter-yield stress loading at the minimum service temperature. It is assumed that this level of performance has been responsible for numerous cases of cracking in ship plate which were repaired without incident. The absence of numerous catastrophic ship failures, on the other hand, is a reflection of good design practice.

A characterization of steel processing techniques and of other metallurgical factors is obviously needed if specifications for a consistent quality hull steel of high toughness are to be established. Most of these factors probably have been well researched by the steel companies. However, development of rational criteria for purchase specifications is still required. For example, a plate of Grade E (U-30) exhibits similar DT performance to plates of Grade C-norm (U-19 and U-93). Yet another Grade E plate (U-28) exhibits superior performance to the other three. The deoxidation practice and heat treatment specified for these grades are identical. Also the specified chemical composition is identical, except for C and Mn. It is readily apparent that variations in C and Mn among the four cited plates does not explain the superior performance of plate U-28. Characterization of weld deposits by different weld processes is also felt necessary for the forementioned reasons.

Finally, the DT trends described here show that different plates within a grade can have DT curves of significantly different shape. Some curves exhibit a sharply rising toughness level within 25° to 50°F above the NDT temperature while others reach this same level of toughness only at 100°F or more above the NDT. Differences in transition behavior may be due in part to heat treatment, deoxidation practice, or residual element levels. Once the causes for such differences are established, a large payoff in structural reliability can be achieved through specifications insuring steels of the former toughness characteristics.

Higher Strength (H) Grades

It is recommended that a DT characterization program, similar to that described here for the ordinary-strength hull steels, be undertaken for the higher strength hull steels (Grades AH, DH, and EH). This study is important if full toughness comparisons are to be established with the ordinary ABS hull grades and if any toughness tradeoffs with a higher yield strength are to be defined.

K_{Id} Trends

If structural performance criteria are to be based on the existence of a given K_{Id}/σ_{yd} ratio at the minimum service temperature as proposed by Rolfe, then the K_{Id} vs temperature trends must be established for the hull steels, as discussed. Application of nonlinear fracture mechanics techniques, such as the J integral, are appropriate for this research.

SUMMARY AND CONCLUSIONS

A program of limited scope to characterize the toughness of ordinary-strength shipbuilding steels has been completed. Random plate samples of production heats of ABS Grades A, B, C, C-norm, D-norm, E, and CS were obtained from various shipyards and steel mills. It is considered that sufficient plates of each grade were investigated to define average properties. However, a more extensive program, statistically based, would be required to define the full extent of properties variation for each grade of steel. The data were presented in the form of NDT temperature, and DT and C_V energy vs temperature curves. Interpretations of the DT curves were expressed in terms of L and YC index values that define, respectively, the upper temperature limit of plane-strain behavior for a given thickness and a yield criterion whereby significant plastic deformation (through-thickness yielding) in the neighborhood of a flaw is required for fracture propagation. Finally, data trends were assessed for the ability of currently produced steels to meet toughness criteria proposed by Rolfe and coworkers in a related Ship Structure Committee project. The principal observations and conclusions made in this investigation were as follows:

1. The NDT temperatures for non-heat-treated Grades A, B, and C exhibited average values of 20°F to 30°F. A trend toward lower average NDT temperatures is indicated for the heat-treated (normalized) Grades C-norm, D-norm, E, and CS. The present data suggest that in most cases a normalize heat treatment will provide NDT temperatures at or below 0°F. A larger variation in NDT temperatures was evident (—40°F to +20°F) for the heat treated grades.

2. All of the steels displayed a high DT upper shelf energy for the longitudinal (RW) orientation. Observed shelf energy levels were sufficient to assure fully plastic fracture behavior in the presence of a flaw. However, the upper shelf temperature range for the majority of the as-rolled steels was 120° to 180°F. The normalized grades exhibited upper shelf performance at temperatures ranging from 0° to 120°F. In general, normal service temperatures for hull materials are not sufficiently high to permit the steels to exhibit their full toughness potential.

3. The full brittle-ductile transition for most 1-in. plates occurred in a temperature interval 90° to 150°F above the NDT temperature. The YC temperature, corresponding to the DT midenergy point was 70° to 110°F above the NDT temperature for the majority of plates. Other observations were

- Absolute YC temperatures for the non-heat-treated grades ranged from 80° to 135°F.

- Normalized grades exhibited absolute YC temperatures from −15° to 95°F, generally below those of the non-heat-treated grades.

- None of the ordinary-strength hull steels will consistently exhibit a YC level of toughness at a minimum service temperature of 32°F.

4. Charpy-V energy values for plates of a given ABS grade tend to exhibit a large variation at the NDT temperature; accordingly, a C_v energy "fix" with the NDT temperature is not feasible. On the other hand, the DT energy levels at NDT exhibited a variation of 300 ft-lb, corresponding to only 5% of the average DT upper shelf energy. The NDT temperature consistently marked the toe of the DT curve, thereby demonstrating that the latter test technique provides a good approximation of the NDT temperature for shipbuilding steels.

5. Adoption of the proposed 0°F NDT criterion for hull steels probably would result in a sufficiently high rejection rate for non-heat-treated steels so that they would cease to be used for this application. Alternatively, use of the normalized grades should enhance fracture-safe reliability.

6. The 5/8-in. DT energy levels projected from 1-in. DT data suggest that the non-heat-treated steels generally will not pass the 5/8-in. DT energy requirement at 75°F proposed by Rolfe (i.e., 250 ft-lb DT energy). However, projections of 5/8-in. DT energy indicate that the normalized grades will meet this requirement in most cases.

7. The proposed 5/8-in. DT energy requirement for arrester plates at 32°F (i.e., 600 ft-lb) probably will not be met by many of the hull grades. However, careful production of Grades E and CS should yield a product that can meet the requirement consistently.

8. A specification requiring only a 0°F (max) NDT temperature does not infer a consistent level of toughness at a fixed service temperature; the additional requirement of DT energy at the service temperature (or some related temperature) is necessary.

Finally, the DT data trends indicate that 32°F (0°C) generally lies in the transition temperature regime of the ordinary hull steels. Arrester materials, in this elastic-plastic toughness regime, may exhibit unstable fracture following a certain degree of plastic deformation. For the newer ship designs it will be of value to demonstrate that the strain tolerance of the arrester material at 32°F (0°C) is greater than that which would allow a postulated fracture of the hull.

ACKNOWLEDGMENTS

The authors express their sincere appreciation to Mr. W. E. Hagel and Mr. M. Martin for conducting the extensive tests and to Mr. H. E. Watson for his helpful assistance in many other experimental aspects of the investigation.

REFERENCES

1. S.T. Rolfe, D.M. Rhea, and B.O. Kuzmanovic, "Fracture Control Guidelines for Welded Ship Hulls," SSC Report 245. Ship Structure Committee, Washington, D.C., pending publication.
2. "Method for 5/8 Inch Dynamic Tear Testing of Metallic Materials," MIL STD-1601 (SHIPS), 8 May 1973.
3. E.A. Lange, P.P. Puzak, and L.A. Cooley, "Standard Method for the 5/8 Inch Dynamic Tear Test," NRL Report 7159, Aug. 27, 1970.
4. *Rules for Building and Classing of Steel Vessels 1972*, American Bureau of Shipping, 45 Broad St., New York, N.Y. 10004.
5. "ABS Project No. G77," revised September 1972, (private communication from Mr. Prakash, ABS, New York, to Mr. Hawthorne, NRL).
6. W.S. Pellini, "Design Options for Selection of Fracture Control Procedures in the Modernization of Codes, Rules, and Standards," Welding Res. Council Bull. 186, Aug. 1973.
7. W.S. Pellini, "Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures," NRL Report 6957, Sep. 23, 1969.
8. W.S. Pellini, "Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels," NRL Report 6713, April 1968.
9. F.J. Loss, J.R. Hawthorne, and W.S. Pellini, "Generalized Procedures for the Use of Plane Strain and Elastic-Plastic Fracture Mechanics Options in the Modernization of Nuclear Standards," NRL Report 7603, Sept. 18, 1973.

10. W.O. Shabbits, "Dynamic Fracture Toughness Properties of Heavy Section A533 Grade B Class 1 Steel Plate," Westinghouse R & D Report WCAP-7623, Pittsburgh, Pa., Dec. 1970.

11. A.K. Shoemaker, S.T. Rolfe, "The Static and Dynamic Low-Temperature Crack-Toughness Performance of Seven Structural Steels," Engrg. Fracture Mechan. 2, No. 4, 319-339 June 1971.

12. F.J. Loss, and W.S. Pellini, "Coupling of Fracture Mechanics and Transition Temperature Approaches to Fracture-Safe Design," in *Practical Fracture Mechanics for Structural Steels*, Chapman and Hall, London, 1969 pp. J1-J35; also NRL Report 6913, Apr. 14, 1969.

13. F.J. Loss, "Engineering Significance of Statistical and Temperature-Induced Fracture Mechanics Toughness Variations of Fracture-Safe Assurance," Trans. ASME, J. Eng. Ind. **95**, Series B, No. 1, pp. 137-144 (Feb. 1973); also NRL Report 7353, Dec. 2, 1971.

14. W.L. Server, A.S. Tetelman, "The Use of Precracked Charpy Specimens to Determine Dynamic Fracture Toughness," UCLA Report Eng. 7153, University of California at Los Angeles, July 1971.

15. R.W. Judy, Jr., and R.J. Goode, "Ductile Fracture Equation for High-Strength Structural Metals," NRL Report 7557, Apr. 3, 1973.

ABBREVIATIONS AND SYMBOLS

SSC — Ship Structure Committee of Maritime Transportation Research Board

ABS — American Bureau of Shipping

NRL — Naval Research Laboratory

ASTM — American Society for Testing and Materials

DW — Drop Weight Test (see ASTM Standard Method E208-69)

NDT — Nil Ductility Transition temperature as determined by the Drop Weight Test

DT — Dynamic Tear Test (see MIL STD — 1601 [Ships])

DTE — Dynamic Tear Energy Absorption (ft-lb, J)

50% DTE — Dynamic Tear Transition Energy corresponding to 50 percent of maximum DT (upper shelf) energy absorption

C_v — Charpy V-notch test (see ASTM Standard Method E23-72)

K_{Ic} — Plane Strain Fracture Toughness, static (psi $\cdot$ in.$^{1/2}$, N $\cdot$ m^{-2} $\cdot$ m$^{1/2}$)

K_{Id} — Plane Strain Fracture Toughness, dynamic (psi $\cdot$ in.$^{1/2}$, N $\cdot$ m^{-2} $\cdot$ m$^{1/2}$)

σ_{ys} — Yield Strength, static (psi, N $\cdot$ m^{-2})

σ_{yd} — Yield Strength, dynamic (psi, N $\cdot$ m^{-2})

RW — Longitudinal Test Orientation, long dimension of specimen is parallel to primary plate rolling direction

RAD — Ratio Analysis Diagram

L — Limit for plane strain (brittle) behavior

L Ratio — K_{Ic}/σ_{ys} ratio corresponding to L index

YC — Yield Criterion, describes the lowest material toughness which permits through-thickness yielding in the neighborhood of a flaw

YC Ratio — K_{Ic}/σ_{ys} ratio corresponding to YC index